Efficient data aggregation and routing in wireless sensor networks

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I would like to dedicate this thesis to my loving brothers and sisters
for their ceaseless support.

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Abstract

Wireless Sensor Networks (WSNs) have gained much attention in a large range of technical fields such as industrial, military, environmental monitoring etc. Sensors are powered by batteries, which are not easy to replace in harsh environments. The energy stored by each sensor is the greatest impediment for increasing WSN lifetime, because power failure of a sensor not only affects the sensor itself, but also its ability to forward packets on behalf of others sensors. Since data transmission consumes more energy than sensing and processing activities, our major concern is how to efficiently transmit the data from all sensors towards a sink. We address this issue by proposing a global solution addressing aggregation, routing as well as channel assignment. We suggest three tree-based data aggregation algorithms: Depth-First Search Aggregation (DFSA), Flooding Aggregation (FA) and Well-Connected Dominating Set Aggregation (WCDSA) to reduce the number of transmissions from each sensor towards the sink. In each proposed algorithm, the degree of connectivity of each sensor is taken into account in the tree construction, by electing sensors having the highest degree of connectivity as parents, and sensors with the lowest as leaves. As a result, aggregated data is efficiently transmitted along the shortest path through multiple hops from parent to parent towards the sink, helping to reduce the number of individual transmissions. Our approach provides local optimization for energy saving that can be used in dense configurations.

Tree-based data aggregation suffers from increased data delivery time because the parents must wait for the data from their leaves. As the network topology varies randomly, some parents might have many

leaves, making it very expensive for a parent to store all incoming data in its buffer. We need to determine the aggregation time each parent in the tree has to spend in aggregating and processing the data from its leaves. Failing to account for aggregation time may lead to a longer waiting time for each parent and increase the overall data delivery latency. We propose an Efficient Tree-based Aggregation and Processing Time (ETAPT) algorithm using Appropriate Data Aggregation and Processing Time (ADAPT) metric. Given the maximum acceptable latency, ETAPT's algorithm takes into account the position of parents, their number of leaves and the depth of the tree, in order to compute an optimal ADAPT time to parents with more leaves, so increasing data aggregation gain and ensuring enough time to process data from leaves. The results obtained show that our ETAPT provides a higher data aggregation gain, with lower energy consumed and end-to-end delay.

At any time, the amount of data aggregated by parents may becomes greater than the amount of data that can be forwarded. To alleviate this, we propose the introduction into the network of many data aggregators called Mini-Sinks (MSs). MSs are mobile and move according to a random mobility model inside the sensor field to maintain the fully-connected network in order to aggregate the data based on the controlled Multipath Energy Conserving Routing Protocol (MECRP). A set of multiple paths is then generated between MSs and sensors in order to distribute the global traffic. We have showed that our original solution can achieve better results in terms of packet delivery ratio, end-to-end delay, network lifetime, and residual energy compared to the single and mobile sink solutions.

Sensors may use many radio interfaces sharing a single wireless channel, which they may use to communicate with several neighbours. Two sensors operating on the same wireless channel may interfere with each other during the transmission of data: packets will be lost and will therefore not be received. We need to know which channel

to use in the presence of multiple channels for a given transmission. We propose a distributed Well-Connected Dominating Set Channel Assignment (WCDS-CA) approach, in which the number of channels that are needed over all sensor nodes in the network in such a way that adjacent sensor nodes are assigned to distinct channels. Parents and leaves are assigned to a single static channel. Mediators, are assigned to several orthogonal channels so that they can dynamically switch to the static channels of the parents to aggregate the data. This allows the data to be efficiently propagated in parallel on multiple channels from the parent to the mediator to the parent towards the sink. Our approach outperforms Sensor Multi-Channel Medium Access Control (SMC MAC) and the single channel in terms of interference, sink throughput, broadcast latency, routing overhead and energy consumption.

Keywords: wireless sensor network, aggregation, multipath, tree-based, degree of connectivity, mini-sink, hybrid channel assignment, radio interface, interference, parents, leaves, mediators.

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Chapter 1

Introduction

Wireless Sensor Networks (WSNs) are seen as a reality, due to the potential applications in various domains [FMLE10a]. A large number of distributed sensors has the ability to gather more detail about the physical environment. The distributed capability of sensors is very important, since data transmission accounts for most energy consumption in WSNs [KTP+11] and [FRWZ07]. Uploading the data directly from each sensor to the sink may result in long communication distances and degrades the energy of sensors. Hence, it makes sense to use local processing as much as possible in order to reduce the amount of data transmitted by each sensor towards the sink. In this chapter, Section 1.1 gives an overview of WSNs. Section 1.2 presents the background and our motivation. Section 1.3 states the research problem and presents the proposition of our thesis. Section 1.4 presents the organization of the rest of the thesis.

1.1 Wireless Sensor Network (WSN)

As shown in Figure 1.1, a WSN consists of a large number of sensors and the sink, which is the final recipient of the sensed information. A WSN can be defined as a distributed wireless ad hoc network consisting of a large number of small devices called sensors, scattered over a particular geographical area for monitoring physical phenomena tracking meteorological changes, seismic activity, movement of enemy troops, industrial monitoring and control etc. A sensor is a device in a WSN that is capable of gathering, processing, communicating with other connected nodes in the WSN. In a WSN, each sensor node is an autonomous

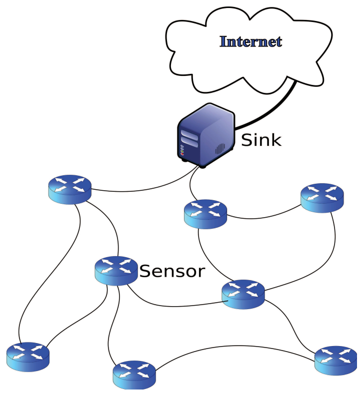

Figure 1.1: Wireless Sensor Network (WSN)

device that consists of communicating, computing, sensing and memory subsystems. A WSN can be considered as a special kind of ad hoc network that consists of a number of sensors spread across a geographical area. Mobile Ad hoc Networks (MANETs) are designed to cope with mobile environments, but can also be applied to handle mobility in WSNs. [ASSC02b] and [WDA10] survey a variety of WSNs and MANETs. Their fundings allow the differences between the technologies to be summarized as follows:

- WSNs are designed for gathering information, while MANETs are designed for distributed computing.
- In MANETs, routing is designed to cope with mobility, while in WSNs, routing is static.
- In WSNs, the number of deployed sensors can be greater than the number of nodes in MANETs.
- The data in WSNs flows from sensors towards the sink, while in MANETs, the data flow is irregular.

- Power resources and memory of sensors could be very limited and are more prone to failure, while nodes in MANETs such as laptops may have significant power resources [BCK11].

- In MANETs, communication is point-to-point, while in WSNs the communication is hop-to-hop due to the limited communication range.

In the following Section, 1.2, we present the background and motivation of this thesis.

1.2 Background and Motivation

The lack of a communication infrastructure brings many challenges in the design of forwarding techniques for WSNs [FMLE10a]. The energy of sensor nodes can be consumed by sensing, processing and communication (transmission and reception) activities. As shown in Figure 1.2, [Est02] shows that data transmission consumes more energy than other activities. Whenever a sensor transmits the data, it consumes a certain amount of energy. Thus, the sensor's energy transmission is the greatest impediment for improving overall network lifetime [AFS09] and [FRWZ07]. The energy constraints of sensors combined with the power required for data delivery leave a clearly defined amount of energy for all other services [KTP+11]. A critical aspect in the design of WSNs is to save energy and keep the network functional for as long as possible. The disconnection of a certain number of sensors causes topology changes in the overall WSN [Fot10].

In this thesis, we address how data are gathered at the sensors, and how data are routed through the network in order to evaluate the impact on network lifetime. Several techniques for managing forwarding data in WSNs such as data aggregation, routing protocols etc, have been proposed in the literature. Data aggregation is the manner to combine more efficiently the data coming from different sources directly towards the sink. Data aggregation techniques focus on utilizing temporal or spatial correlation between sensed data to reduce its quantity [FRWZ07]. In temporal aggregation, the data gathered by sensors changes

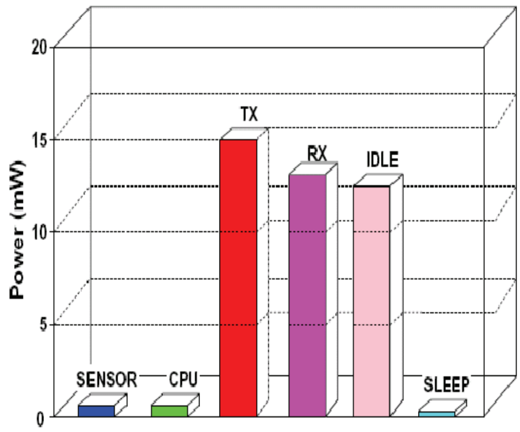

Figure 1.2: Energy consumption level [Est02]

slowly over time, whereas for spatial aggregation, the data gathered by neighbouring sensors is similar.

As all sensors gather and route the data either to other sensors or to an external entity called sink, self-configuration is mandated to give all sensors the possibility of efficiently forwarding data towards the sink. In the most applications, sensors are assumed to be static, allowing the reporting of gathered data in a reactive manner. However, [WT09] show that the static deployment of sensors has many limitations as limited connectivity, battery, storage capacity, etc. Considering the limited connectivity, the deployment of static sensors may not guarantee the whole coverage of the sensing area [KPQT05]. So, the network may be partitioned into several non-connected subnetworks. As sensors are battery-powered, some sensors may die due to the exhaustion of their batteries and may break the network connectivity. The introduction of some mobile elements in the WSN to enhance its limitations could be an interesting solution. Instead of having a central sink responsible for aggregating all the data, introducing multiple mobile data collectors, which are responsible to maintain a fully-connected network topology, aggregate the data and forward it towards the sink. Thus, reducing the congestion appearance and relaxing the requirement on network connectivity.

In our thesis, we propose a complete solution combining data aggregation, an efficient routing of aggregated data and a hybrid multi-channel assignment in radio interfaces in order to achieve long-lived wireless multi-hop sensor networks.

In the following Section, 1.3, we state the problem and present the structure of the thesis.

1.3 Problem Statement and Contributions

1.3.1 Problem statement

As in environmental monitoring, a WSN is designed to gather data throughout some area, these data gathered needs to be made available at a central sink, which is the final recipient of the sensed information. It is typically connected to conventional computing equipment for complex processing of the accumulated readings. The manner in which data is gathered at the sensors, and routed through the network has a great impact on energy consumption of sensor nodes and overall network lifetime. As discussed in [PD07], network lifetime is the difference in time between the deployment of a sensor in a specific area and the time when any sensor fails due to wireless link or power failure. In WSNs, all sensors send their data towards the central sink. This means that communication occurs from many to one (known as convergecast). In this communication mode, the data collection can be made through direct or indirect communication. In direct communication, the sensors upload the data directly to the sink through one-hop wireless communication. Since when sensors transmit data, they use energy in transmission, uploading the data directly to the sink may require with long communication ranges, and so degrade the energy of sensors. Indirect communication, in contrast, the data is uploaded to the sink via multiple intermediate sensors (multi-hop), which results in short communication ranges and guarantees the energy efficiency of the sensors.

- Due to the short wireless communication range of sensors, the sink can only communicate with a limited number of sensors, namely the sensors in the vicinity of the sink (see Figure 1.1). It may happen that some sensors around the sink collect more data because they are aggregating the data from other sensors. Thus, congestion starts to build up on these sensors, and their energy quickly becomes depleted, lead to delays, making them more prone to shutdown. [LSM07] define congestion as the situation in which there is too much data traffic at a sensor that it can be accommodated.

- As each sensor is equipped with a limited amount of storage capacity, at any given moment, some intermediate sensors may fail to receive or transmit further data to the sink, because the amount of data collected becomes greater than the amount of data that can be forwarded. This causes local congestion to emerge at these intermediate sensors, increasing the amount of data loss, so impacting overall network performance [LSM07].

- Sensors may use many radio interfaces sharing a single wireless channel, which they may use to communicate with several neighbors. Two sensors operating on the same wireless channel may interfere with each other during the transmission of data: packets will lost and will therefore not be received [DX11].

Taken together, these considerations lead us to the statement of the problem addressed by this thesis: how to reduce the forwarding rate of the sensors in the network in order to increase network lifetime?

1.3.2 Contributions

Data transmission consumes more energy than sensing and processing as described by [KTP+11] and [FRWZ07]. Instead of minimizing the sensing and computation cost, we propose to reduce the number of data transmissions by each sensor so saving energy in order to achieve long-lived wireless multi-hop networks [AFS09]. The transmission of data by each sensor towards the sink is achieved via intermediate sensors. In our thesis, we propose to design a complete solution combining a powerful tree-based data aggregation scheme, an efficient routing of aggregated data using mobile elements and a hybrid multi-channel assignment in radio interfaces in order to increase network lifetime.

Related to data aggregation issue, we propose three tree-based data aggregation algorithms: Depth-First Search Aggregation ($DFSA$), Flooding Aggregation

(FA) and Well-Connected Dominating Set Aggregation ($WCDSA$) described in Chapter 3. [FRWZ07] show that tree-based is suitable for applications such as environmental monitoring in which the maximum sensor reading received by the sink provides the most useful information. In each algorithm proposed, a tree is built out from the sink. The degree of connectivity of each sensor is taken into account in the tree construction instead of the identifier in order to elect sensors with the highest degree of connectivity as parents (which work as aggregator points), and the sensors with the lowest degree of connectivity as leaves (which work as non-aggregator points). The degree of connectivity of a sensor is the number of incident sensors or links to it. In order to route efficiently the data, the shortest path between each parent and the sink is established. Thus, the number of data transmissions by each sensor in the network remains minimal, and will involve only intermediate parents through the tree from parent to parent towards the sink along the shortest path, which guarantees energy efficiency. For each sink location in the network, we select the best position of the sink in order to obtain the minimum number of packets transmitted towards the sink and of the maximum number of leaves. We compare the performance of our suggested algorithms and the existing Breadth-First Search (BFS), Depth-First Search (DFS) and Flooding in which the identifier of each sensor into account. We have showed that our new suggested algorithms provide appreciably better results.

Related to aggregation time issue, tree-based data aggregation results in increased data delivery time because the parents must wait for the data from their leaves. As the network topology can be random, some parents might have many leaves, making it very expensive for a parent to store all incoming data in its buffer. If a parent waits for the data from its leaves for long time, it collects more data and hence data aggregation gain increases. [RAC04] define data aggregation gain as the ratio of the benefit of traffic reduction due to aggregation to the total traffic generated without aggregation. However, this long wait means that the data delivery time to the sink increases. Thus, it is important to consider the time taken by parents to aggregate and process the data, because it takes more time to aggregate and process the data than to transmit the data towards the sink. Failing to account for the data aggregation and processing time may increase the overall data delivery latency or reduce the data aggregation gain. We propose an Efficient Tree-based Aggregation and Processing Time (ETAPT) algorithm using the Appropriate Data Aggregation and Processing Time (ADAPT) metric as described in Chapter 4. Given the maximum acceptable latency, ETAPT's algorithm takes into account the position of parents, their number of leaves and the depth of the tree, allocating an ADAPT time to parents with more leaves. Thus, increasing data aggregation gain and ensuring enough time to process the data from leaves. We compare the performance of our suggested ETAPT with Aggregation Time Control (ATC) [CLL+06] and Data Aggregation Supported by Dynamic Routing (DASDR) [ZWR+10]. The results obtained show that our ETAPT provides a higher data aggregation gain with lower energy consumed, aggregation time and end-to-end delay compared to the alternative DASDR and ATC methods.

Related to routing issue, during the data aggregation by parents, some intermediate parents may fail to receive or transmit further data because of their limited storage capacity. Deploying many static sinks in the network will be not the solution, as the heavier forwarding load of sensors around the sink will persist. We propose a new and original approach by introducing into the network of several mobile elements called Mini-Sinks (MSs), for aggregating the data as described in Chapter 5. In our network, the sensors and the main sink are fixed, but MSs are mobile. The MSs move inside the sensor field according to a random mobility model to maintain a fully-connected network topology, aggregating the data within their coverage areas based on the controlled Multipath Energy Conserving Routing Protocol (MECRP) [FMLE10a] and forwarding it towards the main sink. MECRP is implemented between sensors and MSs in order to optimize the transmission cost of the forwarding scheme. A set of multiple paths between MSs and sensors is then generated to distribute the global traffic over the entire network. The mobile MSs help to relax the requirement on network connectivity and congestion appearance since the transmission of data from sensors to MSs is done through a single hop. We have compared the results obtained with those for a single and mobile sink proposed by [IKN06]. We have showed that our solution can achieve better results in terms of packet delivery ratio, throughput, end-to-end delay, network lifetime, residual energy and overhead.

Related to channel assignment issue, sensors may use many radio interfaces sharing a single wireless channel, which they may use to communicate with several neighbors. When two sensor nodes operate on the same wireless channel, they may interfere with each other: packets will lost and will therefore not be received. Thus, minimizing interference is crucial for improving network performance. To achieve this, the channel assigned to a particular pair of sensor nodes needs to be distinct from those of nearby pairs. To do this, we need to know which channel to use in the presence of multiple channels for a given transmission. This can be done by determining the number of channels that are needed over all sensor nodes in the network in such a way that adjacent sensor nodes are assigned to distinct channels. We propose a distributed Well-Connected Dominating Set Channel Assignment (WCDS-CA), as described in Chapter 6, in which: a set of parents and leaves are assigned to a single fixed channel. Mediators linking two consecutive parents are assigned to several orthogonal channels. So that they can dynamically switch to the static channels of parents for aggregating the data. The data is propagated in parallel on multiple channels from the parent to the mediator to the parent towards the sink. We compare the performance of our WCDS-CA with Sensor Multi-Channel Medium Access Control (SMC MAC) presented in [RR09] and the single channel methods. The results have showed that our approach outperforms SMC MAC and the single channel in terms of interference, sink throughput, broadcast latency, routing overhead and energy consumption.

In the following Section, 1.4, we present the organization of the rest of the thesis.

1.4 Thesis organization

The rest of the thesis is organized in 6 Chapters as follows.

- Chapter 2 reviews existing approaches to the stated problem. In this chapter, we present the state of the art and recent proposals for standards and protocol architecture for WSNs, data aggregation mechanisms, routing protocols, mobility models and channel assignment in WSNs.

- Chapter 3 presents our new tree-based data aggregation algorithms that aim to reduce the number of transmissions from each sensor towards the sink in WSNs. The degree of connectivity of a sensor is taken into account in tree construction in order to elect the sensor having the highest degree of connectivity as a parent, and the sensor with the lowest as a leaf. As a result, only the set of parents needs to transmit data towards the sink. This reduces the aggregate size of data and the number of individual transmissions towards the sink.

- Chapter 4 presents an Efficient Tree-based Aggregation and Processing Time (ETAPT) algorithm which use a Appropriate Data Aggregation and Processing Time (ADAPT) metric. Given the maximum acceptable latency, ETAPT's algorithm takes into account the position of each parent, its number of leaves and the depth of the tree, in which each parent in the tree computes an optimal ADAPT time before aggregating and processing the data from its leaves. Thus, parents with more leaves will be allocated an appropriate aggregation time, so increasing the data aggregation gain and ensuring enough time to process data from leaves.

- Chapter 5 presents the use of many mobile Mini-Sinks (MSs) instead of a single sink for aggregating data in WSNs. Many mobile MSs move according to a random mobility model inside the sensor field to maintain the fully-connected network in order to aggregate data. The mobile MSs help to relax the requirement on network connectivity and congestion appearance since the transmission of data from sensors to MSs is done through a single hop.

- Chapter 6 presents the multi-channel assignment in multi-radio WSN deployments. In this chapter, a distributed hybrid algorithm to perform a selection of communication channels in a WSN is presented. Parents and leaves are assigned to a single static channel. Mediators, are assigned to several orthogonal channels so that they can dynamically switch to the static channels of the parents. This allows the aggregated data to be efficiently propagated in parallel on multiple channels from the parent to the mediator to the parent towards the sink.

- Chapter 7 summarizes our contributions and sets out our perspectives.

Chapter 2

The State of the Art

In this chapter, we review the state of the art for the problems addressed in this thesis. Section 2.1 reviews some applications of WSNs. Section 2.2 describes the challenges and characteristics of WSNs. Section, 2.3 reviews the standards and protocol stack architecture for WSNs. Section 2.4 reviews the state of the art in data aggregation mechanisms. Section 2.5 reviews the state of the art on routing protocols for WSNs. Section 2.6 moves to the state of the art of mobility models for WSNs. Section 2.7 presents the state of the art in channel assignments for reducing interference. Section 2.8 summarizes the chapter by presenting the advantages and disadvantages of existing approaches.

2.1 WSN applications

As explored by [ASSC02b] and [Fot10], taking into account the communication model, WSNs have potential applications in various domains including:

- Building and habitat monitoring: WSNs could be used to monitor vibrations that could damage the structure of a building, and they can also be used in large buildings to detect and monitor environmental conditions [CEE+01].

- Inventory management: WSNs can provide security in shops, parking garages, warehouses etc. Sensors can be attached to every item of inventory, allowing the tracking of the location of each item at any given time [HKY+06].

- Nuclear, chemical, and biological attack detection: WSNs can be densely deployed in the targeted area and used as a chemical warning system that can be useful to the end users, by helping this type of incident efficiently [EGHK99].

- Medical: Sensors can be attached to the human body to monitor medical issues like, blood pressure, heart rate, and brain activity. They also help medical examiners to better predict and understand the situation of patients by identifying particular symptoms earlier [JMWM04].

- Disaster management: WSNs can be used to map a disaster area, directing the nearest emergency rescue teams to affected sites [AKA11].

- Precision agriculture: WSNs can be used to measure pesticide level in water, and the level of soil erosion to better understanding the agriculture environment [XTS+11].

- Forest fire: WSNs may be deployed in a forest. Sensors can transmit information about the seat of the fire to the fire rescue team before the fire spreads to other areas [PH05].

- Vehicle tracking: WSNs can be deployed to monitor vehicle traffic. The sensors in car parks should be able to detect vehicle locations, sizes, speeds, and road conditions [RV08].

- Military applications: WSNs can be used to detect possible enemy movements, explosions, to monitor opposing forces, friendly forces for battlefield targeting [HKY+06]. Sensors can be attached to every vehicle, allowing status reporting of information to be aggregated in the base station.

In the following Section, 2.2, we present the characteristics and challenges of WSNs.

2.2 WSN Characteristics and Challenges

2.2.1 WSN characteristics

Some characteristics of WSNs as described by [BCDV09] include:

- Small size of sensors: In a WSN, a sensor should small in order to facilitate large-scale and convenient deployment. In some case, sensors may be hidden to achieve undetected surveillance.

- Network size: A WSN should be able to be deployed over small and large-scale area.

- Low cost: A WSN should be cheaper and be able to function even if they are many in the network [MCH09].

- Low resource usage: sensors should be fugal in their use of energy, communication capability, memory capacity, bandwidth, battery lifetime etc.

2.2.2 WSN challenges

[JK04] and [HC09] explored and show that the design of routing techniques in WSNs should have to consider the following features:

- Sensor node deployment

The deployment of a sensor can be manual or random [HC09]. In manual deployment, the sensors are manually deployed at chosen locations and data is routed by sensors through fixed paths. In random deployment, the sensors are deployed randomly at chosen locations [HC09]. [KPQT05] show that an optimal clustering is important to allow full connectivity and energy efficiency of sensors.

- Energy consumption

As data transmission consumes more energy than other activities, the sensor's energy transmission is the main impediment for maximizing the overall WSN lifetime. [Hai09] show that power failure of some intermediate sensors during the transmission may affect the overall WSN lifetime.

- Data forwarding

As all the data gathered by sensors in WSNs are dedicated to the sink, the forwarding of data can be done in time-driven, event-driven, query-driven, and hybrid as described by [HC09] and [LL12]. In the time-driven case, sensors periodically forward the data at regular intervals. This is suitable for applications that require periodic data monitoring as described by [CEE+01]. In the event-driven case, sensors forward the gathered data directly towards the sink. [DADE06] show that this case is suitable for intrusion detection applications. In the query-driven case, the sink generates a query to some sensors in the network, and these sensors forward the gathered data towards the sink based on the query.

- Data aggregation

Due to the fact that some sensors may be close each other during the deployment, some sensors might forward redundant data towards the sink. Data aggregation schemes should be employed in order to reduce the number of transmissions by applying certain functions (minimum, maximum, average, etc) as described by [KEW02b].

- Sensor homogeneous

In a WSN, sensors should have the same capacity in computation, communication, power etc [YKR06] and [HC09].

- Scalability and Fault tolerance

The deployment of sensors in a WSN should be large in order to increase the connectivity between sensors. The design of routing techniques should be adapted to the density of the network in such a way that the overall network performance is not affected. If some sensors fail due to the lack of power, the routing protocols should be able to create new routes in order to forward efficiently the gathered data [HC09].

- Sensor mobility

As described by [VSS10], in most applications, sensors are assumed to be static such as forest monitoring, etc. The mobility of sensors or the sink is important to reduce the congestion appearance in the network.

2.2.3 Sensor node components

As described by [MCH09], the architecture of a sensor typically includes four components: sensing, processing, communication and power as shown in Figure 2.1.

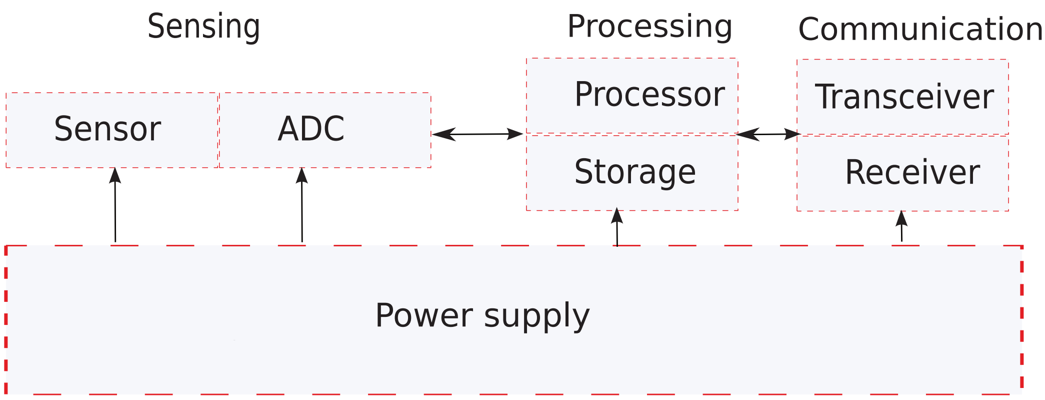

Figure 2.1: Sensor architecture

- The sensing component consists of an internal Analogue-to-Digital Converter (ADC) and one or more sensor sockets, for detecting environmental parameters such as temperature, air quality, illumination, etc. This component links the sensor with the outside world.

- The processing component includes a processor with a micro-controller, and storage to execute local data processing. The processing kit performs networking operations as hop-to-hop routing.

- The communication component consists of wireless transmission and receiver units. It consists of a short range radio for communication.

- The power supply is provided by batteries, or other power sources such as solar energy etc. It supplies energy to the sensor.

In the following Section, 2.3, we present the standard and protocol architecture for WSNs.

2.3 WSN Standards and Protocol Stack Architecture

2.3.1 WSN Standards

[YMG08] define WSN standards as the functions and protocols which help sensors to interfere with a variety of networks. [Wag10] and [YMG08] explore the standard of WSNs, and show that they have been designed taking into consideration the reliable communication with low energy consumption in order to improve network lifetime. Some WSN standards include IEEE 802.15.4, Zig Bee, Wireless Hart, ISA100.11a, IETF 6LoWPAN, IEEE 802.15.3, Wibree and Dash 7 [Nor09].

2.3.1.1 IEEE 802.15.4

IEEE 802.15.4 is used for Personal Area Networks (Pans), which focus on low complexity and energy consumption. [HG03] say that IEEE 802.15.4 is designed for applications that need short communication distance to improve network lifetime. The devices working with this standard are designed to work with physical and data-link layers. Physical layer can operate with 868-868.8 MHz, 902-928 MHz and 2400-2483MHz bands [Wag10]. Some applications of WSNs using this standard are industrial and environment monitoring, control and automation etc.

2.3.1.2 Zig Bee

[IEE03] and [Blu08] define Zig bee as the higher layer communication protocols built on IEEE 802.15.4 standard for low rate Pans. [ZHS03] show that Zig Bee devices are simple to implement, lower cost and use very little power consumption. [YMG08] classify Zig Bee devices into Zig Bee coordinator, Zig Bee router and Zig Bee end device. Zig Bee coordinator is responsible to create the network and store the data. Zig Bee routers are responsible of multi-hop communication among nodes in the network. Zig Bee end device is responsible to communicate with Zig Bee routers. Zig Bee is more suitable in embedded applications [BPC+07].

2.3.1.3 Wireless Hart

Wireless Hart provides a wireless communication for measurement and control applications as described in [Car12]. It is based on IEEE 802.15.4, operates on 2400 MHz and devices are energy efficient due to the use of power management techniques. [YMG08] classify Wireless Hart devices into wireless field devices, gateways, process automation controller and network manager. Wireless field devices connect all devices together in the network. Gateways are responsible for the communication between wireless field devices and the host applications. The process automation controller is responsible to control the process and ensure the security. The network manager manages the communication and the routing among the devices [Wag10].

2.3.1.4 ISA100.11a

ISA100.11a is designed for low data rate, monitoring and automation applications [YMG08]. ISA100.11a focus on low energy consumption, scalability and interoperability with other wireless nodes [ISA09]. [YMG08] show that nodes working with ISA100.11a use only 2400 MHz radio and channel hopping strategy to reduce interference.

2.3.1.5 IETF 6LoWPAN

6LoWPAN provides the communication over a network based on IEEE 802.15.4 [MG07]. With 6LoWPAN, devices can communicate directly with IP devices using IP protocols. [YMG08] show that 6LoWPAN enables an adaptation layer since IPv6 packet sizes are much larger than the size of IEEE 802.15.4. 6LoWPAN is suitable for applications with low data rate that needs Internet to communicate [MKHC07].

2.3.1.6 IEEE 802.15.3

IEEE 802.15.3 is used at the physical and Medium Access Control (MAC) with high data rate wireless Pans [YMG08]. IEEE 802.15.3 operates on a 2400 MHz band with data rate varying between [11-55] Mbps. It uses Time Division Multiple Access (TDMA) strategy to ensure quality of service [Wag10]. This standard is suitable for applications such as video, wireless connectivity.

2.3.1.7 Wibree

Wibree is designed for short-range communication (5-10m) and small power devices such as sensors, keyboards etc [YMG08]. This standard operates on 2400 MHz band with a data rate of 1 Mbps.

2.3.2 Protocol Stack Architecture for WSNs

[ASSC02a] and [OB06] show that the protocol architecture of WSNs consists of physical layer, data link layer, network layer, transport layer, application layer, task, mobility and power management planes as shown in Figure 2.2. Physical layer is responsible of the type modulation used and data communication. The network layer is responsible to route the data through the network and manages the network topology with the help of the transport layer [AFS09]. The data link layer is responsible of assigning communication channels between sensors [AFS09]. The MAC protocol includes in the data link layer helps to reduce the energy consumption of sensors. The transport layer is responsible of data flow depending

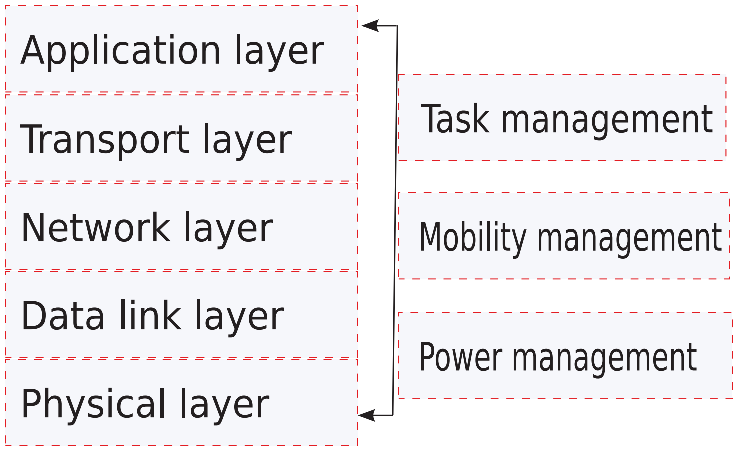

Figure 2.2: Protocol stack architecture for WSNs

on applications [OB06] and [AFS09]. The task management plane is responsible to manage and synchronize the activities among sensors [ASSC02a]. The mobility management plane is responsible to manage the mobility of sensors [OB06]. The power management plane manages the energy consumption of sensors among different activities. It uses the synchronization mechanisms to avoid implosion in order to reduce the energy consumption of sensors. More informations can be found in [AFS09].

In the following Section, 2.4, we present the state of the art and recent proposals for data aggregation schemes.

2.4 Data Aggregation in WSNs

The idea of data aggregation is to combine the data from various sensors more efficiently by eliminating redundant data. [FRWZ07] and [RV06] classify data aggregation techniques into tree, cluster, mesh, chain and hybrid mechanisms.

2.4.1 Tree-based mechanisms

In a tree-based, in which we focus in this thesis, a tree is built out from the sink by electing some special sensors to work as aggregation points. Data is aggregated at intermediate sensors level by level along the tree and forwarded towards the main sink. This mechanism is suitable for applications which involve in-network data aggregation, such as environmental monitoring, where the maximum data values received by the sink provide the most useful information [FRWZ07]. Tree-based data aggregation has some limitations concerning its robustness and maintenance cost. Whenever a packet is lost at a given level of the tree due to link or sensor failures, data coming from the subordinated levels of the tree is lost. A further issue is high cost of maintaining the tree in dynamic networks. Data aggregation using a tree structure has been well-studied in research.

[CLRS01] present Breadth-First Search (BFS) and Depth-First Search (DFS) as two algorithms to explore the graph by building a tree. DFS is a recursive algorithm that explores each branch of the graph to the greatest extent possible. After all links have been explored, it backtracks until it founds a sensor with an unexplored neighbour. In the BFS algorithm, sensor nodes are checked in the order that they are discovered, by maintaining a queue that stores all nodes that have been discovered but not yet processed. At each step, the node at the front of the queue is processed. For example, when the node S is processed, all newly-discovered reachable nodes are added to the end of the queue. At each step of DFS and BFS, the node with greater identifier is processed first. Recall that DFS and BFS explore each link and sensor in the graph exactly once, so the running time of both algorithms is $\mathrm{O}(S + E)$, where S and E are the number of sensors and links respectively. However, the memory usage of BFS depends on the density of the graph, while that of DFS depends on the depth of the graph. [CL02] propose Connected Dominating Set (CDS) to reduce the energy use in the routing by minimizing the number of dominating nodes (parents) necessary to transmit the data. A CDS builds a tree in the graph by locally electing a set of parents in order to minimize the transmission of routing data. The broadcast tree of CDS is constructed incrementally out from the sink via a beacon message, by electing parents and leaves based on Id of nodes. Thus, sensors with the highest identifier are elected as parents, and sensors with the lowest identifier are elected as leaves [GP09]. A CDS of the graph is a set of parents such that any two sensor nodes can communicate with each other via a series of adjacent sensors in the set [FMLE11b]. The broadcast tree defined by the CDS can serve as the communication backbone in the graph. [FLS06] present an approach that uses a spatial aggregation (when the values generated by nearby sensors are similar), and temporal aggregation (when the data sensed by sensors changes slowly over time), to find correlation between sensed data in order to reduce its quantity and hence avoid congestion. [SBLC03] shows that these techniques are especially useful in monitoring applications. [CMT05] propose an additive stream cipher that allows efficient aggregation of encrypted data. The cipher is used to compute statistical values such as mean, variance and standard deviation of sensed data, while achieving significant bandwidth gain. However, they do not address the issue of CPU resource constraint. [PHS00] propose a distributed architecture together with their Border Gateway Reservation Protocol (BGRP) for inter-domain resource reservation. BGRP builds a sink tree for each of the stub domains. This reduces control state memory requirements by aggregating reservations. Consequently, the amount of information that must be propagated between nodes is reduced, so conserving resources. [KEW02b] evaluate the impact of network density on the energy costs associated with data aggregation. However, the time complexity remains unknown in the multi-hop case. [YLL09] propose the first distributed aggregation model based on maximal independent sets to minimize data latency. [GND+05] propose an approach based on the construction of CDSs. The sensors belonging to the broadcast are connected in such a that they can collect data from any sensor in the network.

Other approaches can be found in [CLRS01; CL02; ZWS10; MF08].

2.4.2 Cluster-based mechanisms

In a cluster-based, the network is divided into clusters as described by [YKR06]. Some special sensors, called Cluster Heads (CHs), are elected in order to aggregate the data locally within each cluster and transmit the result towards the sink. The CHs can communicate with the sink directly via long range transmissions or via multi-hops through other CHs [HC09]. The advantages and drawbacks of cluster-based are more or less similar to those of tree-based.

[HCB02] propose Low-Energy Adaptive Clustering Hierarchy ($LEACH$), to provide a balancing of energy usage through random rotation of CHs. In LEACH, some sensors are selected as CHs based on signal strength, and rotate this role among the sensors in the network. No global knowledge is required. The rotation of the role of the CH is conducted in such a way that uniform energy dissipation in the sensor network is obtained. [YG02] present COUGAR as which uses in-network data aggregation to obtain greater energy savings. COUGAR selects a leader node to perform data aggregation and transmit the data to the sink. COUGAR needs extra overhead and energy consumption on each sensor. In COUGAR, leader nodes help to maintain in case of node or link failures. [HC09] show that COUGAR differs from LEACH in the election of leader or cluster head. [YF04] propose Hybrid Energy-Efficient Distributed clustering ($HEED$). HEED is a multi-hop data aggregation method which focus on residual energy and intra-cluster communication. The purpose is to distribute energy consumption to prolong network lifetime, and to minimize energy consumption during the CH selection phase, minimize the control overhead of the network.

2.4.3 Mesh-based mechanisms

Instead of having a tree-based in which each sensor sends its data to a parent, in the mesh-based, one or more alternate path exists between a sender and a destination sensor when the primary path fails [HC09]. These alternate paths are kept alive by sending periodic messages. Data may propagate from the sources towards the sink along multiple paths and data aggregation may be performed by each node. Some drawbacks of this category are extra overhead due to sending duplicates data and the high cost of maintaining the alternate paths.

[CYJ10] propose an approach using a scalable multi-path routing for multiple sinks in wireless sensor networks. Their approach helps to achieve energy efficiency at minimum latency cost. The forwarding mechanism is based on a node's own knowledge, sender guidance and neighborhood knowledge in order to find the shortest possible route with maximum path aggregation. However, the time complexity remains unknown. [NGAS04] propose an approach where data aggregation is performed through a multi-path mesh. The network is organized into rings around the sink, which are formed when a node sends a query over the network. [GGSE01] present an approach which uses multipath to solve path recovery due to the failure of sensors belonging to the path between a source and the sink. Data transmission is done along a single path until it becomes unavailable. [SS03] present a routing algorithm which aggregates data in a robust manner in order to increase network lifetime. [MYH06] propose a multi-path scheme based on multiple spanning trees. In their approach, multiple paths exist between sensors and parents in order to efficiently forward the data. This structure allows duplicate data to propagate, and consequently increases robustness, since multiple copies of the same data are sent along different paths in contrast to tree-based.

2.4.4 Chain-based mechanisms

In a chain-based, sensors are organized into a chain in such a way that each node transmits and receives from only the closest node among its neighbors in contrast to clustering, in which sensors transmit data to the cluster heads where data aggregation is performed [TMZH12]. A chain-based has two major advantages: first, network lifetime is increased by using collaborative techniques among sensors. Second, it requires only local coordination between sensors that are close together, so that the bandwidth consumed in communication is reduced. Unlike LEACH (see Section 2.4.2), PEGASIS avoids cluster formation and uses only one node in a chain to transmit to the sink instead of using multiple sensors.

[TMU06] propose a Chain Oriented Sensor Network (COSEN) for efficient data collection which ensures maximal utilization of network energy and increases network lifetime. Simulation results show that COSEN achieves around 20% better performance than that of PEGASIS in respect of number of rounds before the first sensor dies. [LR02] propose Power-Efficient Gathering in Sensor Information Systems (PEGASIS), where the nodes are organized into a chain. The election of the head node is done by randomly choosing a node from the chain that will transmit the aggregated data to the sink, thus reducing the energy expenditure as compared to the clustering approaches where, if a cluster head is far away from the sensors, it might expend excessive energy in transmission. [DWZ03] propose an energy-efficient chain construction algorithm which uses a sequence of insertions to add the least amount of energy consumption to the whole chain. It also saves about 260% time on average in comparison to PEGASIS. In PEGASIS, only one node is allowed to transmit to the sink at each time, and long delays can be introduced for nodes that are distant on the chain. Since sensors need only to communicate with their closest neighbors and they take turns in communicating with the sink, network lifetime is extended. When the round of all sensors communicating with the sink arrive terminates, a new round will start, and so on. This reduces the power required to transmit data per round, as power drain is spread uniformly over all nodes.

2.4.5 Hybrid-based mechanisms

A hybrid-based combines tree and mesh mechanisms. In a hybrid-based, sensors are divided into two categories: those sensors using a tree mechanism to forward packets and those using a mesh mechanism. The network is organized in sub-regions implementing one of these two mechanisms [SBAG10].

[SZZL07] present an IEEE 802.15.4 standard based low power WSN with Mobile Gateway (MG). MG is use to minimize the network partition. [GBJS08] focus on the software architecture and introduce the network protocol stack of the Linux kernel. [MNG05] propose an approach in which, under low packet loss rates, a tree-based data aggregation is used because of the efficiency that it offers in representing and compressing the data. In the case of high loss rates or when transmitting partial results which are accumulated from many sensor readings, a mesh-based data aggregation is used due to its increased robustness.

In the following Section, 2.5, we present the state of the art and recent proposals on routing protocols for WSNs.

2.5 Routing Protocols in WSNs

One of the main design goals for WSNsans is to carry out data communication while trying to prolong the operational lifetime of the network and prevent connectivity degradation by employing some routing mechanism based on energy management techniques as described in [Fot10]. The design of routing protocols in WSNs is influenced by many challenging factors. These factors must be overcome before efficient communication can be achieved. [AY05] and [AFS09] state that the overall routing techniques taking into account the network structure are classified into data-centric, hierarchical and location-based. Furthermore, these protocols can be classified into reactive, proactive or hybrid routing taking into account the route discovery process [OB06]. In reactive routing, routes are calculated on demand. In proactive routing, routes are calculated before they are needed, while hybrid routing combines both.

In this section, we give a background that discuss routing design issues that affect the routing process in WSNs.

2.5.1 Data-centric

Data-centric is a query-based and depends on the naming of the data desired, which helps to eliminate redundant messages [Fot10].

[WC12] and [DL05] present flooding and gossiping as two techniques to forward data between sensor nodes. In flooding, each node in the network broadcasts to nodes in it neighborhood. Each node receiving the packet, checks if that packet has not broadcast before to rebroadcast. The process stops when all nodes in the network received the packet. [AAFL13] show that flooding suffers from broadcast storm problem which affects network performance. Recall that in flooding, each link in the graph delivers the message one or twice, the message usage is $O(\mid E \mid)$, and the time complexity is $O(D)$, where E and D are the number of links and the diameter of the network respectively. However, gossiping gives only a small low improvement over flooding, since the receiving sensor sends the packet to a randomly-selected neighbor. [RJH99] propose Sensor Protocol for Information via Negotiation (SPIN) that aims to name each packet using meta-data. SPIN advertisement cannot guarantee the delivery of packets if sensors that are interested in specific data are far from its source and intermediate sensors are not interested. SPIN improves on flooding and gossiping in respect of redundancy, overlapping of sensing area. [DL05] present Directed Diffusion (DD), in which the sink uses a list of attribute pairs to broadcast queries to its neighbors, which are capable of aggregation. DD uses only one path among all those discovered to transmit the data until the path fails. Packets are sent via a reinforced path at a high rate. It differs from SPIN in terms of its need for data queries. DD is not suitable for applications that need continuous data delivery.

2.5.2 Hierarchical

Hierarchical protocols divide the network into clusters to efficiently maintain the energy consumption by involving the sensors in multi-hop communication in each cluster, so reducing the number of transmissions to the sink [YKR06].

[RSFG04] present Energy-Aware Routing (EAR) as a routing method that focuses on network survivability by randomly choosing a set of sub-optimal paths, which help to save energy and so increase network lifetime. Since the paths are choose randomly, this provides increases propagation delay during the transmission and hinders the ability for recover in case of node failure. Unlike DD, EAR constrains the ability to recover from a sensor failure. [FPH05] and [PJLR05] present Gradient Based Routing (GBR) as a slightly modified version of DD, which keeps the number of hops to the sink constant once an interest has been expressed. The gradient of the link is the difference between the nodes and neighbors heights. Several paths are created, but the data are transmitted over the path with the largest gradient. [Son05] presents the Low-Energy Adaptive Clustering Hierarchy (LEACH) as an approach that forms clusters of sensors based on received signal strength. Local cluster heads perform aggregation and route packets to the sink. The protocol does not require global knowledge of the network and is not suitable for large-scale networks. Power-Efficient Gathering in Sensor Information Systems (PEGASIS) has been proposed as improvement on LEACH in [Son05]. It differs from LEACH because it uses multi-hop path by forming chains and selecting one sensor to forward to the sink rather than using many intermediate sensors. [AY05] show that Threshold Sensitive Energy Efficient sensor Network protocol (TEEN) is more efficient that LEACH for applications that need periodical reports.

2.5.3 Location-based

Location-based protocols use geographic location information to calculate the distance between two sensors in order to evaluate energy consumption during data forwarding.

[KK04] propose Minimum Energy Communication Network (MECN), which uses low power global position system to identify a relay region. MECN is self-reconfiguring and can dynamically adapt to node failure. It is best suited to static WSNs. [AY05] Geographic and Energy Aware Routing (GEAR) which uses heuristics to forwards packets towards a defined region. They propose in addition Geographic Adaptive Fidelity (GAF) which uses the same principle as DD, but restricts the interest through a defined area.

In this thesis, we focus on data centric routing protocols, because the energy can be saved during data aggregation when the number of sensors is large, and when the sensors are close to each other and far from the sink [KEW02a]. For more detailed information concerning routing protocols in WSNs, we refer you to the survey described by [AY05] and [AFS09].

In the following Section, 2.6, we present the state of the art and recent proposals in the routing using mobile nodes in WSNs.

2.6 Mobility Models for WSNs

Mobility in WSNs introduces many challenges, as described in 2.2.2. [CM10] define several mobility models using a formal mathematical description that generalizes the characteristics of mobility patterns. [BH04] define the mobility models as a formal mathematical description of the movement pattern of mobile users, how their positions velocity change over the time. [Sch06] and [DD11] define mobility patterns as the movement of physical objects, such as vehicles, peoples, which are characterized by the speed, acceleration etc. [PS11] and [SZ09] classify the mobility models in WSNs as memory-based and memory-less models, as shown in Figure 2.3. [BHSW07] show that the mobility metrics that differentiate the two models are: velocity, angle, acceleration, distance between nodes, transmission range, etc.

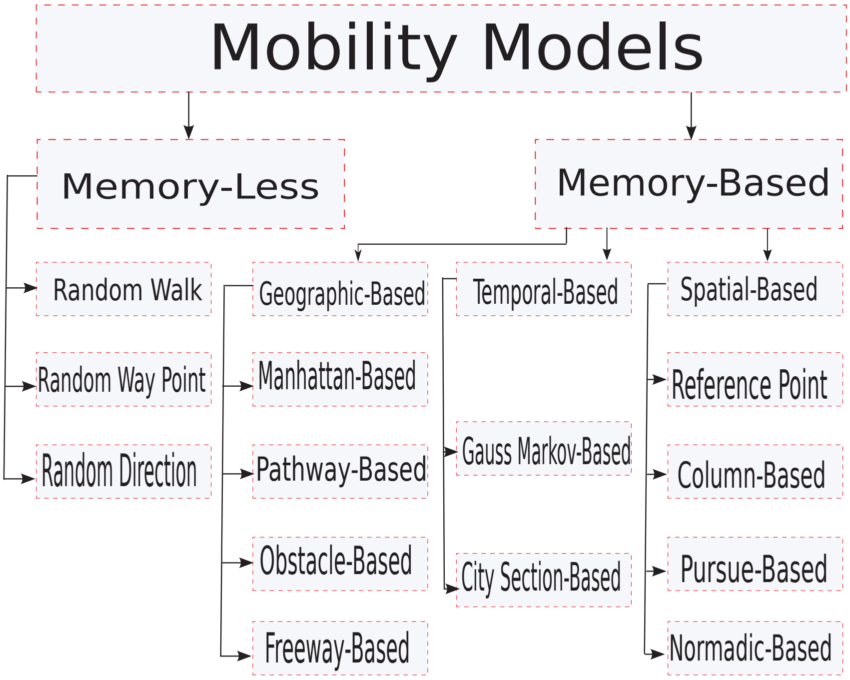

Figure 2.3: Mobility models in WSNs

2.6.1 Memory-Based models

In memory-based models, the mobile sensor uses its previously-stored database to direct its movement. Some examples of memory-based models as described by [BH04] are: Gauss-Markov Mobility (GMM), City Section Mobility (CSM), Geographic Mobility (GM), Manathan Mobility (MM), Freeway Mobility (FM) and Reference Point Group Mobility (RPGM). The GMM works on the previous speed and direction for the current move, and the velocity of the node is modelled as Gauss-Markov stochastic process [LH99]. As described by [HA09], the CSM puts constraints on the movement of a node based on a city street grid. A mobile node moves along the street according to the speed limit. In GM, node movement is restricted to the pathways in the sensing field [BSKH04] and [BH04]. MM is used to emulate the movement of cars in a city [DAGS07]. [DAGS07] show that FM is used for exchanging traffic status or tracking a vehicle on a freeway. As proposed by [HGPC99], RPGM is used in military battlefield communication in which each group has a logical centre, known as group leader.

2.6.2 Memory-Less models

In memory-less models, the mobile sensor does not make use of any memory when changing their locations. Some examples of memory-less models as described in [CBD02] are: Random Walk Mobility (RWM), Random Waypoint Mobility (RWpM) and Random Direction Mobility (RDM). In RWM, a mobile node moves from its current position to a new position by randomly choosing a speed and direction between [speedmin, speedmax] and $[0, 2\pi]$ degree respectively [PS11] and [BMJ99]. RWpM includes pause times between changes in direction and speed. During the mobility of the mobile node, it make a pause time before moving to the new position. Once the pause time expires, the mobile node chooses a random destination with a speed between [0, speedmax] and so on. RWpM is similar to RWM if pause time is zero and [0, speedmax] = [speedmin, speedmax] [BMJ99]. In RDM, a mobile node chooses a random direction instead of a random destination as in RWpM [BH04]. The node travels as far as the boundary of the sensor networks deployment area. When the boundary is reached, the node stops to move for a certain period of time, chooses another angular direction between $[0 , \pi]$ degree, and repeating the procedure indefinitely.

As sensors are limited in memory capacity, we focus on memory-less models in this thesis. In the past, many works have proposed using sensor or sink mobility to collect the data. In the case of the mobile sink, which is the final destination for all the gathered data: the mobile sink moves in order to collect the data from fixed sensors as described in [XCCM08]. In the case of sensor mobility, individual sensors move in the sensing area to collect the data and maintain connectivity among the sensors as described by [CCI+11]. In this chapter, we are interested in the mobile sink, as the mobility of sensors is very complicated in practical WSNs, due to the limited resources of sensors as described in section 2.2.1.

[DD11] classify sink mobility into mobile base station, mobile data collector and rendezvous-based, taking into account the movement pattern of the mobile sink and the manner that the data are collected. In the mobile base station case, [EGB06] explore the consequences of the location of the mobile base station changing as result of movement. The data forwarded by fixed sensors to the mobile base station is relayed towards the sink. In the mobile data collector case, many mobile data collectors are used to collect sensed data from fixed sensors. Rendezvous-based schemes combine a mobile base station and a mobile data collector. In this case, sensors forward the data to rendezvous points close to the path of mobile devices, and the data gathered is stored at rendezvous points until it can be relayed to the mobile sinks. In a WSN, a mobile sink can follow three types of mobility pattern [PS11]: random, fixed or predictable and controlled mobility.

2.6.2.1 Random mobility

With random mobility, mobile data collectors move along a random path within the sensor field and implement a random technique for collecting the data from fixed sensors. Random mobility can be efficient in reducing the appearance of congestion; however, it does not guarantee the collection of data from all sensors and may result in long delays in data delivery.

[IKN06] use random sink mobility to reduce data latency and increase the network lifetime of WSNs. A single sink is moving in a random manner in the sensor field to aggregate the data. The restriction in their approach is that the mobile sink can only gather data from 3 hop neighbors. [GT02] use random mobility of all the nodes to improve data capacity. They prove that two-hop routes are sufficient to achieve the maximum throughput of the network. [SRJB03] propose an architecture for data collection in sparse sensor networks. Their model exploits mobile devices, called MULEs, to collect data from sensors in range, and forward it towards the sink using a random walk mobility model. [VS09] propose the evaluation of various deployment strategies involving sink mobility in the real world in order to reduce energy consumption and propagation delay while increasing network lifetime.

2.6.2.2 Controlled mobility

With controlled mobility, the control of the movement of the mobile data collector is used to increase network performance. The node to be visited is chosen from among those close to the mobile data collector as that with the earliest buffer overflow deadline. Since controlled mobility is used to reduce data latency and increase load balancing, it is less cost-effective than fixed path mobility as explored by [JSS05].

[HC08] explore recent data dissemination techniques using mobile sinks and analyze the impact of mobility on network lifetime. [LNS09] study the theoretical aspects of the uneven energy depletion phenomenon around a sink, and address the problem of energy-efficient data gathering by mobile sinks. [JZD07] propose a model which utilizes context-aware pervasive mobile devices to collect data in a sensor field. [CH03] propose controlled mobility to improve network lifetime and data fidelity. Their idea is to add multiple mobile entities in order to achieve load balancing. [LH05] propose an approach that uses the mobility of the sink in such a way that the sensor nodes located in the vicinity of the sink change over time. They show that combining the mobility of the sink and routing protocols helps to balance the load in order to optimize network lifetime. [KGH07] present the use of a mobile sink to reduce congestion into the network. They use the mobility of mini-sinks according to a controlled mobility pattern in order to aggregate data from fixed sensors. The number of hops is limited, helping to reduce the energy consumption of sensors. [BCPP11] propose a realistically deployable distributed heuristic for coordinating the motion of multiple sinks through the network. They demonstrate that their solution achieves network lifetime significantly greater than those deploying the sinks statically. [WBMP05] propose a novel linear programming model for network lifetime maximization, which governs the movement of the sink rather than minimizing energy consumption at the nodes. Their proposed model results in a fair balancing of energy depletion among the network nodes. [MC09] propose an approach in which mobile sinks change their position when the energy of sensors close to mobile sinks is depleted. The new position of mobile sinks follows the path with the maximum energy of sensors. [WHCY07] propose an energy-aware data aggregation scheme for transmitting data to a mobile sink. Their approach is based on a grid in which each sensor with location information and limited energy are considered. In the region of interest, the gateway which has the highest residual energy is chosen as the root. Each of the other sensors chooses its parent sensor among its neighbors based on information about its residual energy and distance to the root. Therefore, the gateway which will has more residual energy can connect to more neighboring gateways, so distributing energy consumption and increasing network lifetime.

2.6.2.3 Fixed path mobility

In fixed path mobility, the mobile data collector moves along a fixed path. In this case, all sensors should know the movements of data collectors in order to forward the data, helping to improve overall network performance. However, whenever the mobile data collector moves, routing paths need to be updated with a consequential high routing and energy overhead.

[VVZF10] propose an approach that combines a probabilistic flooding strategy to collect data. [YYS06] propose the use of mobile sinks to route data towards the destination via the shortest paths. Residual energy is taken into account in the shortest paths calculation in order to maximize network lifetime and reduce overhead. [CCA09] study the effects of sensor node mobility on the formation of networks conforming to IEEE 802.15.4/Zig Bee. They authors focus on both single-sink and multi-sink configurations to analyze network performance as a function of the number of sinks. [LPP+06] propose an approach that uses a routing protocol to balance the energy dissipation and reduce the amount of data loss. The discrete mobility of the sink is used, where the sink pause time is greater than its mobility time. [PBH07] propose the use of a reactive sink mobility concept for data collection by implementing a novel gradient-based routing protocol in order to improve the fault tolerance and load balancing.

In the following Section, 2.7, we present the state of the art and recent proposals in channel assignment in WSNs.

2.7 Channel Assignment in WSNs

Much research has been done in the area in channel assignment in WSNs. [DX11] divide channel assignment in WSNs into static or quasi-static, dynamic and hybrid strategies.

2.7.1 Static assignment

Considering static or quasi-static assignment, [SGD+07] and [TXZ05] propose a mapping between a wireless channel and a wireless link for long-term use. This method can be subdivided into common and varying channel assignment approaches. In common channel assignment, the radio interfaces of every sensor are all assigned the same set of channels. In varying channel assignment, the radio interfaces of different sensors may be assigned to different sets of channels. Thus, increases network throughput. However, the static assignment of channels may generally incur high overheads, and nodes must have a global knowledge of the network. Static assignment can also lead to network partition and topology changes that may increase the length of paths between the sensor nodes. Consequently, management of topology changes needs to be carried out carefully.

[MDS10] propose a graph-theoretic formulation of channel assignment using a novel topology control perspective. They also develop a new greedy heuristic channel assignment algorithm for finding connected, low interference topologies by utilizing multiple channels. [KLL11] suggest a cross-layer approach that selects appropriate channels for each mesh node to use with carefully-tuned transmitter power, and computes the optimal multicast flows from multiple cooperative gateways. Simulation results show that their proposed solution provides high throughput for multicast routing. [RR09] propose Sensor Multi-Channel Medium Access Control (SMC MAC) to alleviate the hidden terminal problem. Hidden terminal is when two nodes that are out of range of one another, both transmit on the same channel at the same time, resulting in interference and data loss at a common receiving node. The performance of their method gives better results than a single channel in terms of throughput and latency. [WSHL08] propose a greedy algorithm in which the network is divided into subtrees. They allocate different channels to each subtree, and then forward each data packet along its corresponding subtree; this is suitable for use when the number of channels is small. [WM10] evaluate three popular types of static channel assignment on a wireless mesh network. They show that routing protocols must be modified to take advantage of static channel assignment techniques. [JDM11] propose a cross-layer approach to joint channel assignment and construct a multicast tree based on binary integer programming to minimize the impact of hidden terminals. The authors achieve promising results, although their method is distributed and fairly complex, incurring high overheads when the density of the network increases.

2.7.2 Dynamic assignment

Considering dynamic assignment, [BCD04] and [DAVR05] propose changing the channel on the interface frequently. Consequently, when nodes need to communicate with each other, a coordination mechanism is needed to ensure they are on a common channel. The benefit of dynamic channel assignment is the ability to switch an interface to any channel, thereby gaining the potential of using many channels with few interfaces. The challenges involve channel switching delays and the need for coordination mechanisms for channel switching between sensor nodes. However, [CB04] show that the fast switching of the channel makes theses techniques not suitable for use with the commodity hardware in which the delays during the switching can be greater.

[JX11] propose a network restoration solution via the joint design of traffic rerouting, channel re-assignment, and scheduling over a multi-radio multi-channel wireless mesh network. They provide a greedy static edge to channel assignment algorithm, where a channel is initially assigned to a graph edge and remains fixed over all time slots. [RBAB06] propose an approach to handle channel assignment for radios instead of links. However, the interference problem remains unsolved. [GGCS10] propose a link layer algorithm that continually learns channel characteristics and dynamically decides when to switch between radio interfaces. Based on the results obtained from a practical analysis, they achieve up to 52% energy saving compared to when a single channel is used. [SRSL11] propose a new multichannel allocation protocol for Zig Bee WSNs. Their approach is based on the availability of multiple channels, allowing to dynamic tuning to different frequencies in order increase the number of simultaneous transmissions on adjacent links. However, their approach does not perform well with multi-hop.

2.7.3 Hybrid assignment

Hybrid assignment in which we focus in this thesis, combines static and dynamic assignments by applying a fixed assignment for some interfaces and a dynamic assignment for others. Approaches can be sub-classified based on whether the fixed radios use a common or a varying channel.

[RRT+11] propose a hybrid method which they call interference and traffic aware channel assignment. Their approach performs efficient multi-hop routing between every node and the designated gateway nodes by reducing intra-flow and inter-flow interference among the network nodes. [KV06] propose a link layer protocol based on a novel assignment strategy to manage the use of multiple channels. Fixed interfaces are assigned to fixed channels for long intervals of time, while switchable interfaces can be switched more frequently among the non-fixed channels to maintain connectivity.

In the following Section, 2.8, we summarize the chapter.

2.8 Summary

In this chapter, we have presented the state of the art and recent proposals in standards, data aggregation, routing, mobility models and channel assignment in WSNs. In Section 2.3, we saw that WSN standards include IEEE 802.15.4, Zig Bee, Wireless Hart, ISA100.11a, IETF 6LoWPAN, IEEE 802.15.3, Wibree and Dash 7.

In Section 2.4, we classified data aggregation schemes into tree, mesh, cluster, chain and hybrid mechanisms as shown in Table 2.1. In this thesis we have proposed three simple and efficient tree-based data aggregation algorithms. We have chosen tree-based approach because it is suitable for applications such as environmental monitoring in which the maximum sensor reading received by the sink provides the most useful information. In each proposed algorithm, a tree is built out from the sink taking into account the degree of connectivity of each sensor instead of the Id of a sensor. Thus, electing sensors having the highest degree of connectivity as parents, and sensors with the lowest as leaves. As a result, aggregated data is efficiently transmitted along the shortest path through multiple hops from parent to parent towards the sink, helping to reduce the number of individual transmissions. Our proposed tree-based data aggregation algorithms performs well in a dense networks in which the data generated traffic is not high.

Mechanisms	Functions	Advantages	Disadvantages
Tree	Data size reduction, Lossy and Lossless	Medium scalability, Medium resilience of link failures	High cost of maintaining tree, Low robustness, No energy savings
Cluster	Data size reduction, Signal strength	Medium overhead, Energy savings, Local route repairs	Low scalability, Low resilience in mobility
Mesh	Duplicate sensitive, Duplicate insensitive	High scalability of links, High resilience in mobility, High robustness	High overhead, high cost of maintaining alternate paths
Chain	Data size reduction	Energy savings due to the rotation of leader node	High delay, Low resilience of links, Low robustness, Low resilience in mobility
Hybrid	Data size reduction, Duplicate sensitive, Duplicate insensitive	High resilience of links, Medium overhead, Medium scalability	No energy savings

Table 2.1: Classification of data aggregation structures in WSNs

In Section 2.5, we classified routing protocols for WSNs into data-centric, hierarchical and location-based as shown in Table 2.2. In this thesis, we focus on data-centric routing because it helps to eliminate redundant messages during the transmission in order to improve network performance.

Protocols	Characteristics
	DATA centric
Flooding	Overhead due to duplication, overlapping of sensing
Gossiping	Low overhead, high delay
Direct Diffusion	Not suitable for applications that need continuous data delivery
SPIN	No overhead and overlapping, but not suitable for applications that need continuous data delivery
	HIERARCHICAL
LEACH	Low overhead, less energy consumption than gossiping and flooding, and not suitable for large area
TEEN	High overhead, suitable for applications that need periodic data delivery
GBR	Low overhead, overcomes Gossiping and Flooding
PEGASIS	Local coordination between sensors that are close together, avoids cluster formation, only one node in a chain to transmit to the sink
	LOCATION-based
MECN	Can dynamically adapt to node failure, suitable for fixed sensors
GEAR	Reduces the energy consumption, not scalable and does not support data diffusion
GAF	Not suitable for applications that need continuous data delivery, balance of energy consumption among sensors
SLURP	Uses approximate geographic and source routing to reach the destination, which needs high power consumption

Table 2.2: Classification of routing protocols for WSNs

In Section 2.6, we saw that the mobility models in WSNs can be classified as memory-less and memory-based models. In the memory-less models that are the focus of this thesis, taking into account the mobility pattern, the mobile data collector can implement random, controlled and fixed mobility as shown in Table 2.3. As our approach deals with addressing both aggregation, routing and channel assignment. In the following Chapters 3, 4, 5 and 6, we will present in detail respectively our tree-based data aggregation schemes, our efficient routing protocol for aggregated data using mobile elements and finally multi-channel assignment scheme.

Pattern	Characteristics	Advantages	Disadvantages
Random	Random path	Low congestion	No guarantee of the collection of all data
Controlled	Controlled path	Low latency and Good load balancing	Less cost-effective than fixed path
Fixed	Fixed path	Low latency and Low energy consumption	Need to update the routing paths, and high routing overhead

Table 2.3: Classification of mobility patterns

Section 2.7 concludes by presenting the classification of channel assignment into static, dynamic and hybrid types as presented in Table 2.4. In this thesis, we focus on a hybrid assignment in which a set of parents and leaves are assigned to a single fixed channel. Mediators linking two consecutive parents are assigned to several orthogonal channels. So that they can dynamically switch to the static channels of parents. Thus, aggregated data is propagated in parallel on multiple channels from the parent to the mediator to the parent towards the sink.

In the following Chapter 3, we present in detail our new tree-based data aggregation schemes.

Strategy	**Channel**	**Advantages**	**Disadvantages**
Static	Common and varying channel	Unchanging connectivity of the network, high throughput	Network partitions, topology changes increase the length of path between nodes
Dynamic	Scheduling links to channels	Ability to switch to any channel	High switching delays, need coordination mechanisms between nodes, not suitable for use with current commodity hardware
Hybrid	Fixed and dynamic channels	Simple coordination algorithms	High switching delays

Table 2.4: Classification of channel assignment strategies

Chapter 3

Tree-based Data Aggregation Schemes

Data aggregation in WSNs is an energy conservation technique which attempts to reduce the size of transmitted data by locally collecting the data at intermediate sensor nodes and applying aggregation operation in order to transfer only the most useful results towards the sink. In this chapter, we present our motivation in Section 3.1 and define the problem to be addressed. Section 3.2 presents our new tree-based data aggregation algorithms. Section 3.3 presents the simulation set-up and comparative results, while Section 3.4 summarizes the chapter.

3.1 Motivation

Over the last few years, WSNs have been perceived as an alternative solution for communication in a large range of technical fields [FMLE10a]. The self-configuring nature of ad hoc networks makes them suitable for several applications areas such as environmental monitoring etc. The lack of a communication infrastructure brings many challenges in the design of communications techniques for these networks. Each sensor is equipped with a limited amount of storage, and is able to communicate with its neighbours over wireless connections. In hostile environments, where it is often difficult to replace the sensor batteries, self-configuration is mandatory in order to maintain the network's functionality as long as possible.

Numerous techniques for managing forwarding data in WSNs have been proposed in the literature. The idea of data aggregation is to combine more efficiently the data coming from different sources directly towards the sink. In WSNs, data is usually collected by sensors throughout some area, and needs to be made available at a central sink, which is typically connected to conventional computing equipment for complex processing of the accumulated readings. Data aggregation techniques focus on utilizing temporal or spatial correlation between sensed data to reduce its quantity [FRWZ07]. In temporal aggregation, the data gathered by sensors changes slowly over time, whereas for spatial aggregation, the data gathered by neighbouring sensors do not vary much over time [SBLC03]. [FLS06] show that spatial aggregation try to find correlations amongst the data received from different sensors with the goal of reducing the traffic load and appearance of congestion. [GP09] state that minimizing the amount of data is known to be NP-hard problem. In our work, we focus on spatial data aggregation, using in-network data aggregation, in order to reduce the quantity of data transmitted.

3.1.1 Problem statement

Let consider the network topology as shown in Figure 3.1, consisting of many sensors and a single sink. All sensors need to transmit the gathered data towards the single sink. Every time a sensor transmits a data packet, energy is consumed and the battery is depleted. Thus, communication (transmission) is a primary source of energy depletion in WSNs.

Each sensor periodically makes measurements, and forwards its data towards the sink. When area covered becomes too large, some sensors may be far away from the sink and will need the help of intermediate sensors for their data to reach the sink. Due to the short wireless communication range of sensors as described in Section 2.2.1, the sink can only communicate with a limited number

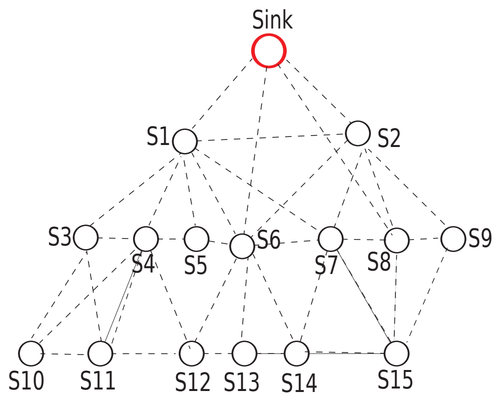

Figure 3.1: Wireless Sensor Network (WSN)

of sensors, namely those in the vicinity of the sink. Some sensors around the sink may collect more data because they are aggregating the data from other sensors. Thus, congestion starts to build up on these sensors, and the energy in these sensors quickly becomes depleted, degrading network performance.

The problem addressed in this part of our thesis is how to reduce the number of individual transmissions by each sensor in the network.

3.1.2 Tree-based Data Aggregation

To alleviate the problem described above, we need to know how data are gathered at the sensors, and how data are routed through the network in order to evaluate the impact on the overall network performance. As data transmission consumes more energy than sensing and processing. Our idea for reducing the energy consumption is to reduce the amount of data transmitted from each sensor by reducing the number of sensors necessary to transmit the data. To achieve this, we employ data aggregation techniques. When an event occurs, sensors sense and forward successive data items towards the sink via intermediate sensors, which eliminate local redundancy and transmit only the necessary data towards the sink. We propose three tree-based data aggregation algorithms: Depth-First Search Aggregation ($DFSA$), Flooding Aggregation (FA) and Well-Connected Dominating Set Aggregation (WCDSA). Our motivation to use a tree-based is because it is more suitable for applications which involve in-network data aggregation, where data concerning maximum values provides the most useful information when received at the sink [FRWZ07].

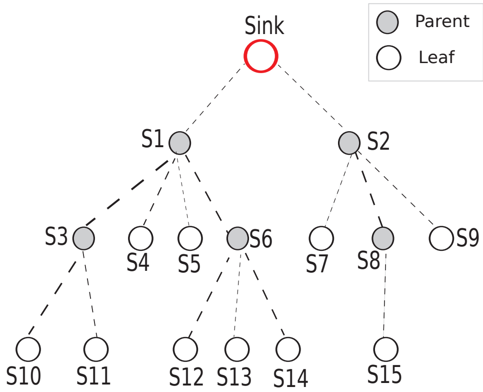

Figure 3.2: WSN: Tree construction

In each algorithm proposed, the tree is built out from the sink as shown in Figure 3.2, taking into account the degree of connectivity of sensors to direct the aggregation policy in order:

- to elect sensors with the highest degree of connectivity as parents, and the sensors with the lowest degree of connectivity as leaves.
- to establish the shortest path between each parent and the sink.
- to minimize the data transmitted on the network, as it is propagated from parent to parent along the shortest path towards the sink.

3.1.3 Illustration

To better understand the effect of the sensors' degree of connectivity, let consider a simple topology consisting of five sensors annotated with their degree of connectivity, and a single sink as shown in Figure 3.3(a). Let d(s_i), be the degree of connectivity for a given sensor s_i. i is the number of links incident to s_i. Let (M_i (i = 1....5)), be the set of data gathered by each sensor. In conventional propagation, as shown in Figure 3.3(a), each sensor should transmit as shown in

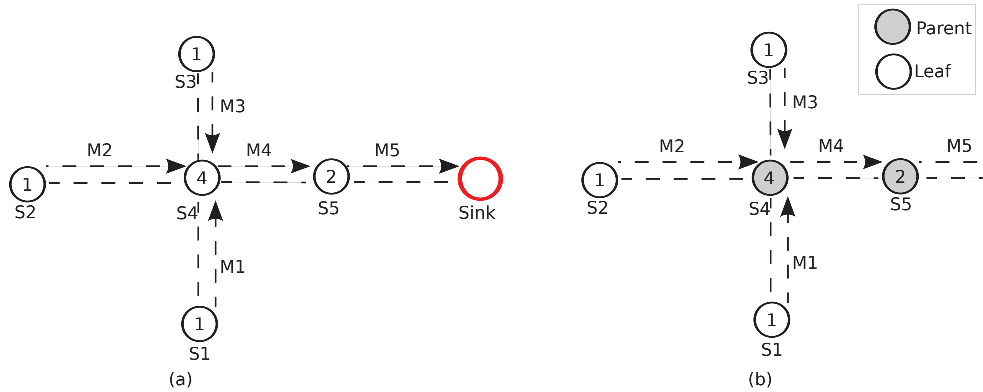

Figure 3.3: Effect of sensor's degree of connectivity

Table 3.1. The total number of transmissions between sensor nodes towards the sink in the following routing paths is 12.

S_1	S_4	S_5	Sink
S_2	S_4	S_5	Sink
S_3	S_4	S_5	Sink
S_4	S_5	Sink	
S_5	Sink		

Table 3.1: Routing Table from each sensor towards the Sink

Figure 3.3(b) shows how the tree is built out from the sink by electing the sensors having the highest degree of connectivity as parents, and those with the lowest degree of connectivity as leaves. We randomly and uniformly choose a delay time varying between [0 - T]. T represents the time that each sensor performs before to receive and process data packets. When T expires, the sensor aggregates all incoming data packets into one, which is sent over a single link as follows:

$$\{S_1, S_2, S_3\} \rightarrow S_4$$
$$\{S_4\} \rightarrow S_5$$
$$\{S_5\} \rightarrow Sink$$

In this manner, the total number of transmissions is reduced to 5 instead of the 12 needed by a conventional scheme. Thus, selecting the sensors with highest degree of connectivity as parents and the lowest as leaves helps to reduce the total number of transmissions towards the sink as a consequence reduces the overall energy consumption of each sensor.

In the following Section, 3.2, we sate the assumptions of our work and present the our new tree-based data aggregation algorithm.

3.2 New Tree-based Data Aggregation Algorithms

This section is related to *[FE09; FMLE10b; FMLE11b]*.

3.2.1 Assumptions

We state the assumptions of our work as follows:

- Sensors are deployed over an area of size L.
- Sensors are homogeneous (same computing, memory capacities,...) and have fixed locations.
- A single fixed sink is the final recipient of all the gathered data.
- Each leaf node has one parent that is responsible for forwarding the received data towards the sink.
- Leaves can only sense and transmit their measurements to their parents.
- Each sensor keeps track of its own degree of connectivity value $\mathrm{d}(s)$.
- Each sensor node maintains a list of the identifies (Ids) of its neighbours.
- Aggregation of multiple packets results in one packet.

3.2.2 Network model

Our proposed WSN consists of low power sensors and can be modelled as a unit-disk connected graph $G = (S, E)$, where S is the set of N sensors and E is the set of wireless links between any two sensors. G_i (i = 1,.....,i), the set of partial graphs. Let v be a subset of S. We denote by $D(S_i, S_j)$, the Euclidean distance between a pair of randomly-chosen sensor nodes (S_i, S_j). P, a path connecting any two sensor nodes.

Lemma 1. *It is always possible to enumerate the nodes of all connected graphs $G = (S, E)$ under the form $x_1, ..., x_n$ such that the set of partial graphs G_i restricted to nodes $\{x_1, ..., x_i\}$ is connected for all i.*

Proof. Take any node $x_1 \in S$, and suppose by induction that $x_1, ..., x_i$ have been chosen for a certain i $<$ $\mid S \mid$. Let us then choose a node $y \in\ G - G_i$. According the hypothesis, G is connected, thus $\exists$ a path P connecting y to x_1. We decide to choose x_{i+1} as being the last node of P in $G - G_i$. By construction, we know that x_{i+1} has a neighbour in G_i. The degree of connectivity of each G_i ensues by induction on i. □

3.2.3 Depth-First Search Aggregation (DFSA) algorithm

$DFSA$ consists of three mayor phases: tree construction, data forwarding and tree recovery phases.

- Phase 1: Tree construction

The construction of $DFSA$ is similar to DFS at each step, except that the sensor with the highest degree of connectivity is explored first. The sink starts to explore its two neighbours S_1 and S_2 as shown in Figure 3.4.

The sink chooses S_2 as current node because d(S_2) $>$ d(S_1), and then sends a request message containing three entities: the sensor Id, the degree of connectivity value d(v), and the Time To Leave (TTL). When S_2 receives the message from the sink, S_2 chooses in its local neighbourhood the sensor with the highest degree of connectivity S_5 as current node, records it Id and degree in the message, decreases the TTL value before to send the message. Propagation continues step

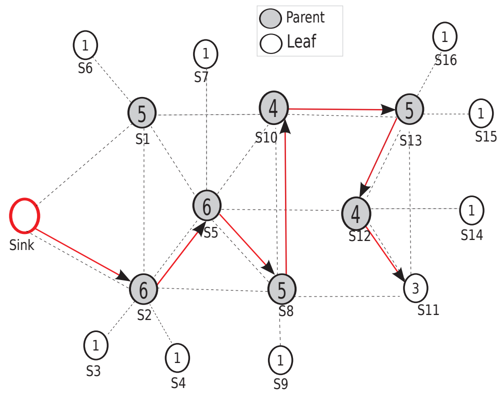

Figure 3.4: DFSA: Tree construction

by step at node S_2 as shown this sequence:
$S_2 \longrightarrow S_5 \longrightarrow S_8 \longrightarrow S_{10} \longrightarrow S_{13} \longrightarrow S_{12} \longrightarrow S_{11}$. When the message reaches node S_{11}, it stops because all its neighbours S_8 and S_{13} have already been visited. The sensor S_{11} initiates a beacon and send to S_{12} to inform that the propagation has been stoped because all its neighbours have already been visited. This beacon is sent back from S_{12} towards the sink in the sequence:
$S_{13} \longrightarrow S_{10} \longrightarrow S_5 \longrightarrow S_2 \longrightarrow Sink$. Once the sink receives the beacon, initiates the bactracking on the sensor S_1, and iterates the propagation in depth until all nodes have been visited. During the propagation of the message, each node stores the sensor Id and the degree of connectivit d(v) value for all visited nodes in its routing table. When the process is complete, each sensor node knows its unique predecessor in the tree. Nodes with the highest degree of connectivity and at least one leaf are elected as parents or aggregators and nodes with the lowest degree of connectivity and without leaves are elected as leaves. We recall that the algorithm is centralized by the sink as it knows the overall network topology, but distributed by each sensor as each sensor chooses its parent based on its local neighbourhood.

- Phase 2: Data forwarding

In the resulting tree obtained previously, we want to forward efficiently the data. As in a dense network, many parents may be connected with other parents. In order to know precisely which parent to send the data, we have used *Dijkstra's* *algorithm* in order to extracted the shortest path between parents and the sink (Algorithm 1). Thus, data transmission takes place from parent to parent towards the sink along the shortest path in order to reduce the number of individual transmissions by each sensor.

```
Input: G = (S, E), V = S, NeighborsList = ∅, sink, depthTree
Output: Tree construction and forwarding.
while V ≠ ∅ do
    choose any Sensor u ∈ V = V.FirstSensor;
    V.RemoveFirstNode;
    Sensor with greater degree is processed first;
    for all Leaves ∈ NeighborsList do
        if Leaves are unvisited then
            choose u as parent;
            then, set Leaves to visited;
            V.addFirstSensor;
        end
    end
end
n = length (pred) ;
NbpacketsDFSA ⟵ length (predDFSA) - 1;
for i = sensor do
    path = RoutingDijkstra (length, i, sink);
    depthTree = max (depthTree, length (Path) - 1);
    if (depthTree (find (data (V (l), 1 : data (V (l))) = k))= 0) then
        data (V (l)) ⟵ data (V (l)) + 1;
        NbpacketsDFSA = (NbpacketsDFSA length (Path) - 1);
    end
    NbpacketsDFSA ⟵ sum (NbpacketsDFSA);
end
```

Algorithm 1: Pseudo-code for DFSA

- Phase 3: Tree recovery

During the transmission of data, it might happens that at any given level of the tree, a leaf or a parent fails due to link failures or when the energy of a sensor becomes 0. During the tree construction phase, each sensor stores in it routing table the degree of connectivity of all the sensors in it local neighbourhood. Thus, when a leaf elects the first node having the highest degree as it parent, consider the other as alternatives. Thus, in the case of link failures, each leaf will directly checks in its routing table in order to elect the new node with the greater degree of connectivity as it new parent in order to forward the incoming gathered data. The analysis of tree recovery will be done in our short term future work.

3.2.4 Flooding Aggregation (FA) algorithm

FA consists of two mayor phases: tree construction, data forwarding and tree recovery phases.

- Phase 1: Tree construction

In order to construct the tree in FA, we start by the Pure Floofing (PF) in which the sink starts by sending a request message to both its direct neighbours S_1 and S_2. The message contains two entities: the sensor Id and the Time To Leave (TTL) value. Each node in the network receiving the message, checks if that message has not broadcast, records it Id in the message, decreases the TTL value before to rebroadcast to sensors in its neighborhood. This to avoid that a sensor receives several times the same message. This propagation scheme is repeated until all sensor nodes have been reached as shown in Figure 3.5. In order to elect parents and leaves, we have analyzed all common sensor between all paths. For each connection between a sensor and the sink in the network, we evalute the number of times that each sensor is traversed by a path during the phase of PF initiated by the sink. The result is stored in a connectivity map. Based on the connectivity map, we select sensors with a highest connectivity level as parents, otherwise they are leaves.

- Phase 2: Data forwarding

In order to forward the data from the resulting tree, the shortest path between parents and the sink is determined using *Dijkstra's algorithm*. Thus, data transmission takes place from parent to parent along the shortest path towards the

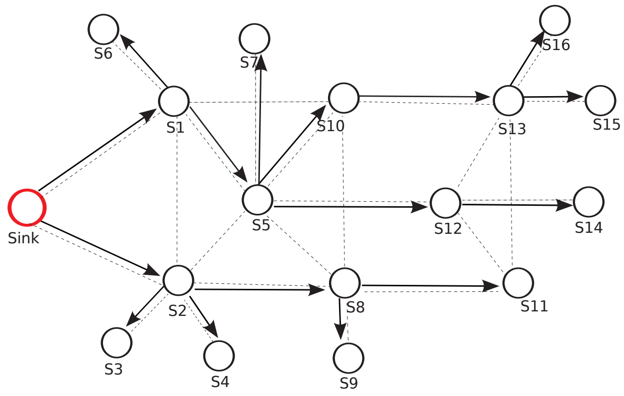

Figure 3.5: FA: Tree construction

sink in order to reduce the number of individual transmissions (see Algorithm 2). FA provides a slight improvement over PF because data can be sent in an efficient manner along the tree. Consequently, network load is decreased by reducing the number of packets transmitted from each sensor towards the sink.

Input: Connected graph $G = (S, E)$; sink, Congestionmap, TTL
Output: Tree construction and forwarding.
sensor = 1 : n;
sensor $\longleftarrow$ Remov (sensor, sink);
predFlood = (1, n);
Congestionmap = (1, n);
for $i = sensor$ **do**
  Path = RoutingDijkstra (length, i, sink);
  Nbpackets (i) = length (Path) - 1;
  Congestionmap (Path) $\longleftarrow$ Congestionmap (Path) + 1;
  if *length (Path)* $\neq$ *2* **then**
    predFlood(i) = Path (2);
  end
  predFlood (i) = sink;
end

Algorithm 2: Pseudo-code for FA

- Phase 3: Tree recovery

During the transmission of data, it might happens that at any given level of the tree, a leaf or a parent fails due to link failures or when the energy of a sensor becomes 0. During the tree construction phase, each sensor stores in its routing table the Id of nodes having a highest connectivity level from it local neighbourhood. Thus, when a leaf elects the first node having the highest connectivity level as it parent, consider the other as alternatives. Thus, in the case of link failures, each leaf will directly checks in it routing table in order to elect the new node with the highest connectivity level as it new parent in order to forward the incoming gathered data. The analysis of tree recovery will be done in our short term future work.

3.2.5 Well-Connected Dominating Set Aggregation (WCDSA) algorithm

$WCDSA$ consists of two mayor phases: tree construction, data forwarding and tree recovery phases.

- Phase 1: Tree construction

Since the construction of $WCDSA$ is based on the Connected Dominating Set (CDS), we first outline CDS. When nodes cannot modify their communications range in the network to save energy, the simple way to reduce energy use in routing is to minimize the number of dominating nodes (parents) necessary to transmit the data. The broadcast tree of CDS is constructed incrementally out from the sink via a request message, by electing parents and leaves based on degree of connectivity as shown in Figure 3.6(a). Thus, sensors with the highest degree of connectivity are elected as parents, and sensors with the lowest degree of connectivity are elected as leaves. A CDS of G is a set of parents S' ($S' \subseteq S$), such that every sensor in $S - S'$ is in the neighbourhood of at least one node in S', and the set of parent S' is connected. As shown in Figure 3.6(a), the broadcast tree defined by the CDS can serve as the communication backbone in G, because it ensures that every sensor node is adjacent to the set, and any two sensor nodes can communicate with each other via a series of adjacent sensors in the set [FMLE11b] and [GP09].

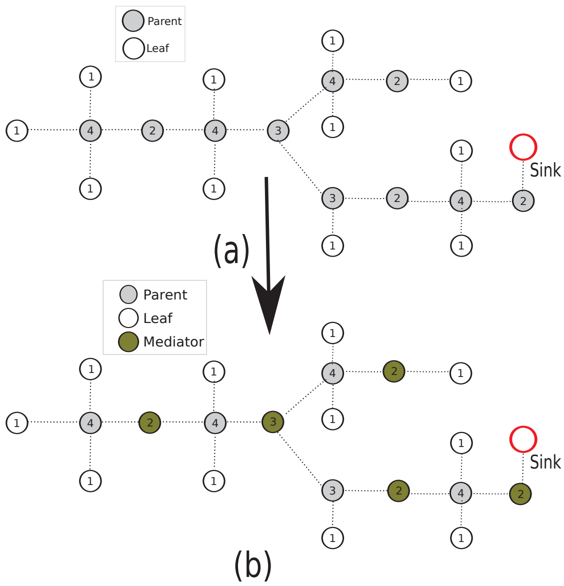

Figure 3.6: WCDSA: Tree construction

$WCDSA$ computes the minimum number of parents in S'. After constructing the tree as shown in Figure 3.6(a), electing sensors with the highest degree of connectivity as parents, and sensors with the lowest degree of connectivity as leaves. Some specific common sensors, called mediators, linking two consecutive parents are elected as shown in Figure 3.6(b). A mediator serves as router during forwarding procedures. From Figure 3.6(a)-(b) we note that the total number of parents necessary to cover the network, the cardinality of

$$| WCDSA |= 5 \leq | CDS |= 10 \tag{3.1}$$

- Phase 2: Data forwarding

To efficiently forward the data, the shortest path between parents and mediators is established using *Dijkstra's algorithm*. This allows the data to be efficiently propagated along multiple hops from parent to mediator to parent towards the sink, helping to reduce the number of individual transmissions (see Algorithm 3).

```
Input: Connected graph G = (S, E), sink, length
Output: Tree construction and forwarding.
Initially , V = S, CDS (S) = ∅.
while V ≠ ∅ do
    take any v ∈ V;
    CDS (S) = CDS (S) ∪ v;
    V = V \ (v ∪ N(v));
end
S' ⟵ CDS;
for all u, v ⊆ CDS do
    S' = S' ∈ Path;
    Path = RoutingDijkstra (length, sink)
end
Parent = 1 : n;
for i = 1: length (Parent) do
    Leaf = Remov (Leaf , Parent(i));
    WCDSA ⟵ WCDSA find (Parents (i));
end
```

Algorithm 3: Pseudo-code for WCDSA

- Phase 3: Tree recovery

During the transmission of data, it might happens that at any given level of the tree, a leaf or a parent fails due to link failures or when the energy of a sensor becomes 0. During the tree construction phase, each sensor stores in it routing table the degree of connectivity of all the sensors in it local neighbourhood. Thus, when a leaf elects the first node having the highest degree as it parent, consider the other as alternatives. Thus, in the case of link failures, each leaf will directly checks in its routing table in order to elect the new node with the greater degree of connectivity as it new parent in order to forward the incoming gathered data. The analysis of tree recovery will be done in our short term future work.

In the following Section, 3.3, we present simulation set-up and comparative results.

3.3 Simulation set-up and Comparative results

In this section, we describe the simulation set-up and followed by presenting of the comparative results.

3.3.1 Simulation set-up

Evaluations of BFS, DFS and our proposed $DFSA$, FA and $WCDSA$ described above were implemented in Scilab, an open-source software package for numerical computation. It is released under the CeCILL license and available under different operating systems [Gom06]. We analyzed each method for different network sizes varying from 50 to 500 sensors, randomly deployed in a square area 1000m x 1000m. The parameters of analysis are described in Table 3.2. Since the euclidean

Table 3.2: Simulation parameters

Parameters	Description	Value
L	Simulation area	1000m x 1000m
P_{Length}	Packet length	2 Kbits
Traffic rate	UDP traffic	5 packets/sec
MAC	MAC layer	IEEE 802.11b
R	Locality radius (m)	30m
$SIMU_{Time}$	Simulation time	900s
N	Number of sensors	[50-500]

distances between sensors, $D(S_i, S_j)$, are also randomly distributed for different pairs of (S_i, S_j), a direct connection between two neighbouring sensors (S_i, S_j) is possible if and only if $D(S_i, S_j) \leq R$. Each sensor generates a data every 5s. In order to validate our analysis, we repeated the experiments ten times with the same topology, with 95% confidence interval. The averaged value of these ten runs are presented.

3.3.1.1 Evaluation criteria

Since the sink is the final recipient of the sensed information, it location is crucial to efficiently receive the gathered data. The scope of our simulation is restricted to studying the effect of sink location on aggregation efficiency across many topologies. We suppose that each sensor in the network can be the sink. Thus, for all the 193 sensors, we vary the position of the sink. We compare the performance of our suggested algorithms as presented in Table 3.3. This analysis allows us to select the best position of the sink in order to obtain:

- the minimum number of packets transmitted by sensors to the sink in G.
- the maximum number of leaves in G.

Technique	**Tree criteria**	**Performance**
DFS	Node Id	Number of relay nodes
BFS	Node Id	Number of relay nodes
DFSA	Node degree	Number of leaves and transmissions
FA	Node congestion level	Number of leaves and transmissions
WCDSA	Node degree	Number of leaves and transmissions

Table 3.3: Performance criteria

A short description of BFS and DFS has been given in Chapter 2, Section 2.4.1.

3.3.2 Comparative results

Let consider the network topology consisting of 193 sensors with 513 wireless links as shown in Figure 1. Each sensor in the network generates a packet every 3s. We simulated the WSN with different positions of the sink in order to find the best location as shown in Figure 3.8.

- Evaluation of the minimum number of packets transmitted by all sensors to the sink.

Figure 3.9 shows how the minimum number of packets transmitted by each sensor to the sink varies with the transmission method and the sink location. The

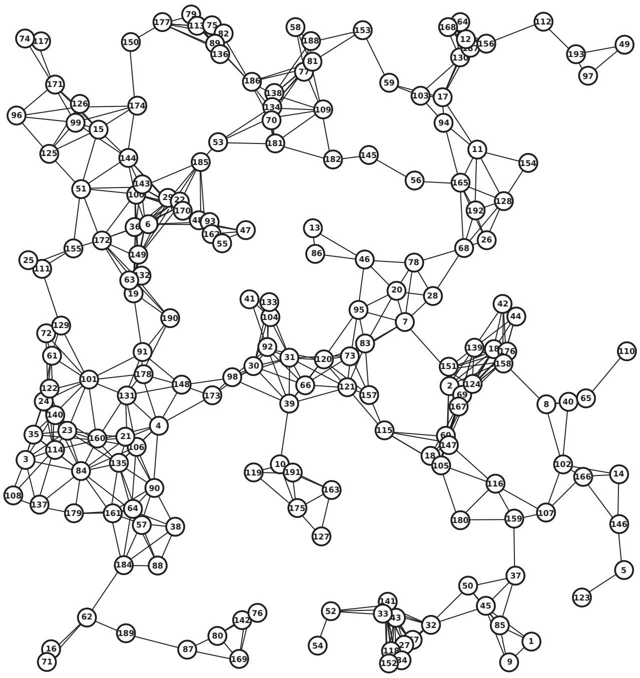

Figure 3.7: Network topology consisting of 193 sensors

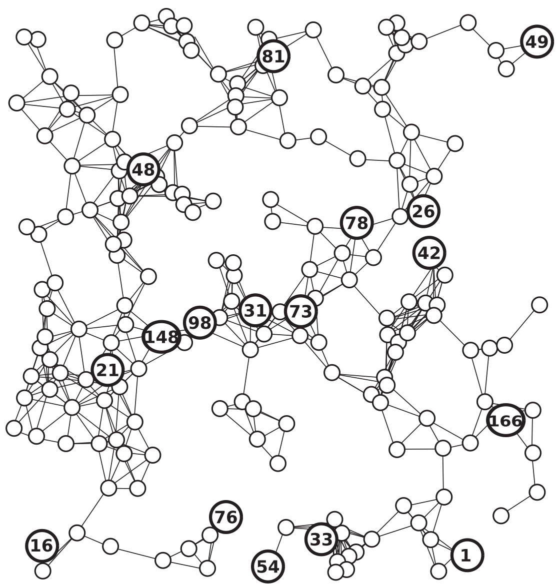

Figure 3.8: Network topology consisting of 193 sensors with different locations of the sink

figure 3.9 shows that DFS and $DFSA$ present the worst results with around 2785 and 2670 packets, with the sink located at nodes 78 and 31 respectively. An improvement is seen with $WCDSA$, BFS and FA with around 1121, 1167 and 1441 packets when the sink is located at nodes 148, 98 and 73 respectively. That is due to the use of mediators and parents during the transmission of data. Table 3.4 provides statistical results for minimum, maximum and mean number

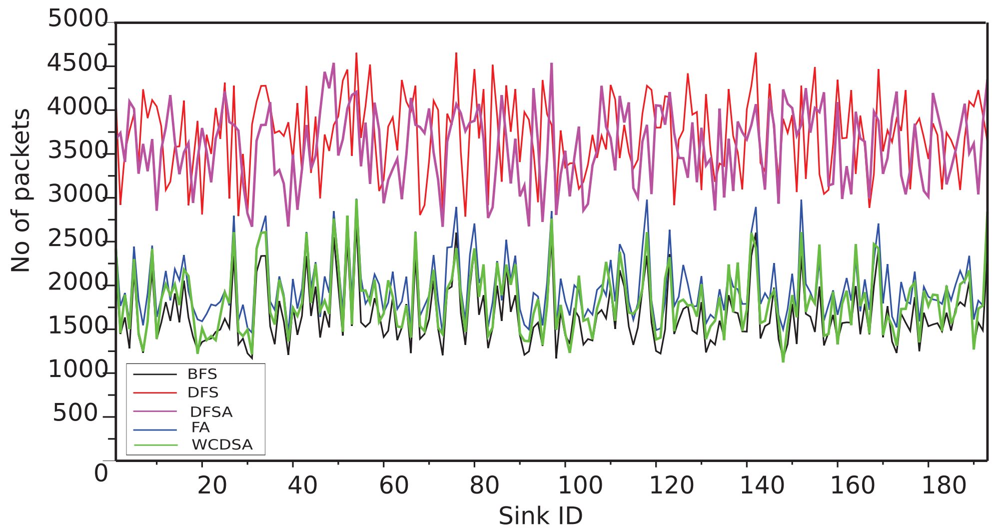

Figure 3.9: Number of packets in each method

of packets transmitted for each method. We can see that BFS, $WCDSA$ and FA outperform $DFSA$ and DFS with the lowest mean numbers of packets of 1663, 1830 and 1979 packets respectively. Because, BFS, $WCDSA$ and FA have fewer number of parents than $DFSA$ and DFS, so transmit less packets.

- Evaluation of the maximum number of leaves in G.

In terms of maximum number of leaves, Figure 3.10 shows that FA and BFS give the worst results with respectively around 50% and 58% of leaves with the sink located at node 33 for FA and node 166 for BFS. DFS and $DFSA$, with respectively around 61% and 63% of leaves, with the sink located at nodes 48 and 21, present an improvement over FA and BFS. The maximum leaf count is

Methods	Min	Sink	Max	Sink	Mean Packets
BFS	1167	98	2714	54	1663
DFS	2785	78	4657	76	3715
DFSA	2670	31	4539	49	3599
FA	1441	73	2988	54	1976
WCDSA	1121	148	2982	54	1830

Table 3.4: Statistical results for the number of packets for each position of the sink

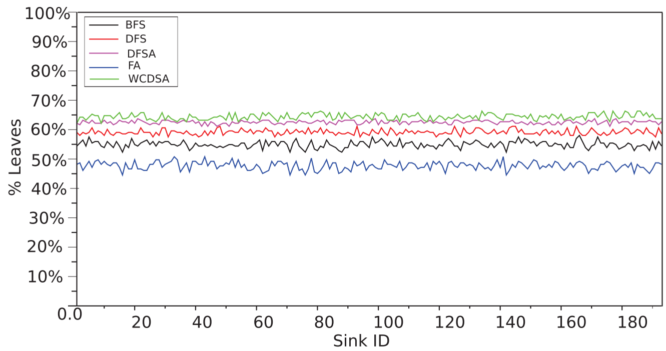

Figure 3.10: Ratio of leaves for each method

achieved using $WCDSA$, which gives around 66% of leaves with the sink located at node 81.

Table 3.5 provides statistical results for minimum, maximum and mean of the number of leaves for each method. We can easily see that in terms of mean value, FA presents the worst results with around 47% of leaves. An improvement over FA is achieved by BFS and DFS with around 54% and 59% of leaves respectively. $DFSA$ and $WCDSA$ outperform FA, BFS and DFS with a mean of 62% and 64% of leaves.

In order to understand the behaviour of our methods in dense networks, we randomly select a fixed position for the sink, and evaluate the average number of packets transmitted and the percentage of leaves in G for different numbers of sensors. Figure 3.11 shows that, the density of the network varies between $[100 - 500]$ sensors, BFS, FA and $WCDSA$ outperform $DFSA$ and DFS with an average of 2310, 2841 and 4485 packets respectively. In terms of average

Method	Min	Sink	Max	Sink	Mean Leaves
BFS	52	16	58	166	54
DFS	57	26	61	48	59
DFSA	61	42	63	21	62
FA	44	16	50	33	47
WCDSA	62	1	66	81	64

Table 3.5: Statistical results for the number of leaves for each position of the sink

percentage of leaves, the Figure 3.12 shows that, as the density of the network varies between $[100-500]$ sensors, $WCDSA$, $DFSA$ and DFS outperform BFS and FA with an average of 78.94%, 76.74% and 74.72% of leaves respectively. That is due to the fact that the degree of connectivity implies the number of incident sensor, and helps to maximize the number of leaves in order to reduce the number of parents.

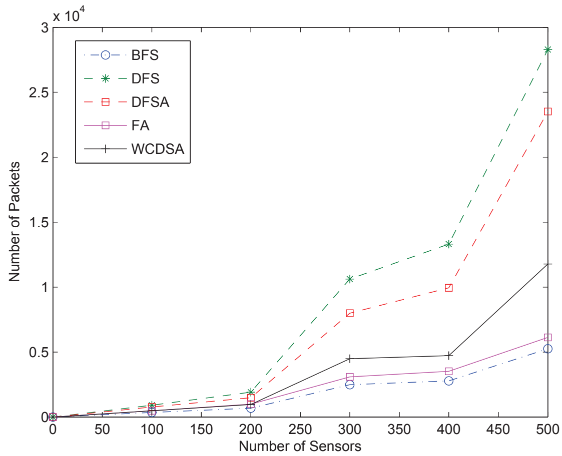

Figure 3.11: Average number of packets in each method

In the following Section, 3.4, we summarize the chapter.

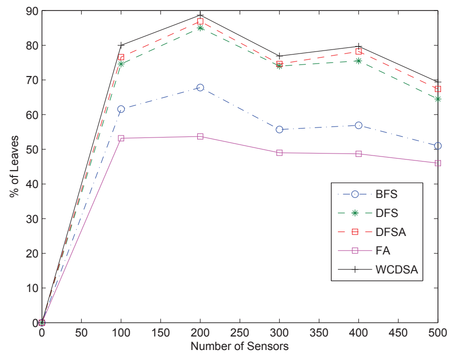

Figure 3.12: Average percentage of leaves in each method

3.4 Summary

There are many algorithms centralized and distributed, for maximizing the number of leaves in network graphs. In this chapter, we have suggested three new tree-based data aggregation algorithms, $DFSA$, FA and $WCDSA$, that aim to reduce the number of transmissions from each sensor towards the sink in WSNs. The degree of connectivity of a sensor is taken into account in tree construction in order to elect the sensor having the highest degree of connectivity as a parent, and the sensor with the lowest as a leaf. As a result, only the set of parents needs to transmit data towards the sink. This reduces the aggregate size of data and the number of individual transmissions towards the sink, and maximizes the number of leaves. Simulations were performed, taking into account the minimum number of packets transmitted towards the sink and of the maximum number of leaves as performance criteria. We have showed that the new suggested algorithms provide appreciably better results than existing algorithms such as BFS, DFS, flooding and CDS as shown in Table 3.6. Our suggested algorithms are particularly useful in resource-constrained networks since each sensor does not need to have global knowledge of the entire network topology and perform well in a dense networks in which the data traffic generated is not heavy. However, as the sink is the final recipient of all the gathered data. We have seen that the position of the sink has a great impact on network performance, because among all the algorithms evaluated, none performs well for the same position of the sink.

	DFS	BFS	DFSA	FA	WCDSA
Tree-criteria	Node's Id	Node's Id	Node's degree	Node's connectivity	Node's degree
Topology	Uniform	Uniform	Uniform	Uniform	Uniform
Performance criteria	Number of relays	Number of relays	Number of transmissions and leaves	Number of transmissions and leaves	Number of transmissions and leaves
Advantages	No need global knowledge	No need global knowledge	Load decreased, lifetime increase	Load decreased, lifetime increase	Load decreased, lifetime increased
Disadvantages	No energy saving	No energy saving	No resilience of node failures	No resilience of nodes failures	No resilience of nodes failures

Table 3.6: Comparison

The resulting tree constructed of BFS, DFS, $DFSA$, FA and $WCDSA$ with each sink location can be seen in Appendix 7.2.

Due to the fact that data gathered by sensors could be similar, in the short term: we will consider the correlation of data transmitted in order to mitigate the problem of reporting similar data by close sensors. We will evaluate the energy consumption during data aggregation by parents. We will evaluate the impact on the overall overhead in the network. In the long term issue, we will take into account the tree maintenance. Whenever a packet is lost at a given level of the tree due to link or sensor failures, data coming from the subordinated levels of the tree is lost.

In Chapter 4, we propose an Efficient Tree-based Aggregation and Processing Time (ETAPT) algorithm, which uses a metric called Appropriate Data Aggregation and Processing Time (ADAPT) to compute an optimal delay for a parent before aggregating and processing the data from its leaves.

Chapter 4

Efficient Tree-based Aggregation and Processing Time

In the previous chapter, we saw that tree-based data aggregation could be an efficient technique for reducing the number of individual transmissions by each sensor in the network. As the sink must receive the data from all sensors, it is important to forward the data in a timely manner towards the sink. We address in this chapter the time taken by parents to aggregate and process the data from their leaves. We first present our motivation and related work in Section 4.1. Section 4.2 states the problem and presents our proposal. Section 4.3 presents our model and describes notation. Section 4.4 presents our approach. Section 4.5 presents performance metrics and comparative results and Section 4.6 summarizes the chapter.

4.1 Motivation

In WSNs, each sensor covers a defined area, collecting local data and sending it towards the main sink. It may happen that some sensors deployed in the monitored area sense common data. Consequently, much energy will be wasted if all this data is forwarded towards the sink. We have seen in Chapter 3 that data aggregation based on a tree structure is an efficient technique for conserving energy [FRWZ07] and [FMLE11b]. As the sink must receive the data from sensors in a timely manner, this data aggregation has a relationship with the data aggregation time. We need to determine the data aggregation time that each parent in the tree should spend in aggregating the data sent from its leaves. Failing to account for data aggregation time may lead to a longer waiting time for each parent and increase overall data delivery latency. The promptness with which data is delivered to the sink indicates better network performance.

4.1.1 Related works

As our WSN focuses on gathering the data from the environment, it is important to forward the data towards the sink in a timely manner. Several approaches have been proposed concerning an optimal data aggregation delay. In this section, we briefly describe some previous work in the field.

[ZWR+10] propose Data Aggregation Supported by Dynamic Routing (DASDR) in which sensors that monitor events are concentrated in space as far as possible and data packets flow to the sink along different paths. Dynamic routing builds a depth field, that aims more efficient data aggregation process. Results show that DASDR helps to obtain a high data aggregation gain, saves energy and scales well with network size. [CLL+06] propose dynamic Aggregation Time Control (ATC) based on the number of leaves. ATC allocates more aggregation time to sensors having more children to increase data aggregation gain. However, ATC is not suitable to multi-hop sensor networks since it requires global knowledge of the network. In addition, the broadcast scheme used during the construction of the tree needs a high communication overhead and decreases network performance. [SO04] propose an approach in which sensors schedule their time-outs based on their position in the tree. Their approach does not need a centralized control. However, they do not take into account the number of children in each sub-tree, leading to traffic congestion. [QK08] compute the data aggregation time-out for clustered WSNs. The time-out is computed based on the packet transmission and cascading delay. [SPS10] develop an approach which delivers the data to the sink within the deadline. They estimate the time-out of each sensor in the tree, so that the data generated by each sensor is delivered to the sink before the deadline. [CTL11] propose to construct a centralized and decentralized structure in the network in order to reduce the transmission delay during the collection of data. [LZZ12] propose a Delay-minimized Energy-efficient Data Aggregation (DEDA) algorithm to minimize data aggregation latency. The physical distance between sensors is taken into account in DEDA to save the transmission energy and energy consumption is balanced among the nodes in order to improve network lifetime.

Our proposal is based on the one used by [ZWR+10] and [CLL+06]. However we take into account the position of parents, their number of leaves and the depth of the tree, in such a way that parents with more leaves will be dynamically allocated an appropriate aggregation time, so maximizing the data aggregation gain and improving network performance.

In the following Section, 4.2, we state the problem addressed in this chapter and present our proposition.

4.2 Problem statement and Proposition

4.2.1 Problem statement

In our context (spatial aggregation), the data gathered by sensors that are close to each other do not vary much over time. Tree-based data aggregation results in increased data delivery time because the parents must wait for the data from their leaves. Since the network topology can be random, as shown in Figure 4.1, some parents may have many leaves, making it very expensive for a parent to store all incoming data in its buffer. [CLL+06] show that if a parent waits for the data from its leaves for a long time, it collects more data and hence Data Aggregation Gain (DAG) increases. DAG is the ratio of traffic reduction due to aggregation to the total traffic without aggregation. However, this long waiting time means that the data delivery time to the sink may increase. Thus, it is important to consider the time taken by parents to aggregate and process the data, because it takes more time to aggregate and process the data than to

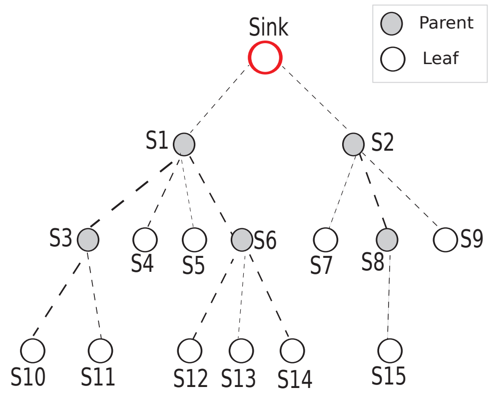

Figure 4.1: WSN with leaves and parents

transmit the data towards the sink. Lacking of attention to the data aggregation and processing time may increase the overall data delivery latency or reduce the DAG.

The problem addressed here is to determine the data aggregation time each parent in the tree should spend in aggregating and processing the data from its leaves?

4.2.2 Proposition: ETAPT algorithm

We propose an Efficient Tree-based Aggregation and Processing Time (ETAPT) algorithm using the Appropriate Data Aggregation and Processing Time (ADAPT) metric to calculate the data aggregation and processing time for parent nodes as shown in Figure 4.2. Given the maximum acceptable latency, ETAPT's calculation takes into account the position of parents, their number of leaves and the depth of the tree, in order to compute for each parent an optimal ADAPT before aggregating and processing the data from its leaves. So, allocating an appropriate aggregation time (Agg_{Time}) to parents with more leaves in order to increase the DAG, thus ensuring enough time to process the data from leaves.

In the following Section, 4.3, we present the network model and describe the notations.

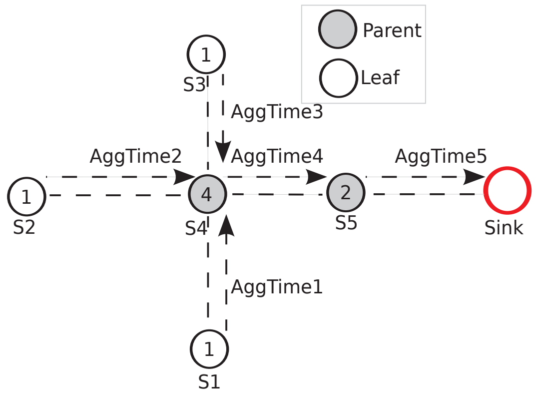

Figure 4.2: Distribution of aggregation time

4.3 Network model and Notation

4.3.1 Network model

The proposed WSN can be modelled as a connected graph $G = (S, E)$, where S is the set of N fixed sensors, and E is the set of wireless links. We use the locality model suggested in [ZCD97] to determine network connectivity. The probability of a link between two sensor nodes S_i and S_j is given by:

$$P = \begin{cases} 1 \ if \ D(S_i, S_j) \leqslant R \\ 0 \ if \ D(S_i, S_j) > R \end{cases} \tag{4.1}$$

Where $D(S_i, S_j)$ is the Euclidean distance between sensors S_i and S_j, and R is the locality radius.

4.3.2 Assumptions

We assume in our approach that:

- Sensors are deployed in an area of size L.
- Sensors are homogeneous (same computing, memory,...) and fixed.

- Each sensor maintains a list of the identifies (Id) of its neighbours.
- Each sensor keeps track of its own degree of connectivity value $d(s)$.
- Each leaf has one parent that is responsible for forwarding the received data towards the sink.
- Leaves can only sense and transmit their data to their parents.
- Aggregation of multiple packets results in one packet.
- A single sink is the final recipient of all the sensed data.
- T_{max} is the maximum acceptable latency.

4.3.3 Notation

Let $s \in S$. Let Path (s_1, s_k) be the sequence: $s_1, s_2 ... s_k$. We define $Hop_{Distance}(s_1, s_k)$ $= k - 1$ as the number of hops from sensor s_1 to s_k. Let $d(s)$ be the degree of sensor s. δ is the minimum transmission time between two sensors of the same $Hop_{Distance}$ in the tree, and ensures that there is a difference in the waiting times at consecutive $Hop_{Distance}$ of the tree. We define:

$$L_{EAF} = s \mid s \in S, d(s) = 1 \tag{4.2}$$

as the set of leaves in the tree,

$$M = S - L_{EAF} - sink \tag{4.3}$$

as the set of parents in the tree, and

$$Hop_{Distance}(s) = d(s, sink) \tag{4.4}$$

as the number of hops of the Path (s, sink). We recall that $Hop_{Distance}$ (sink) $= 0$. Let the depth of the tree be:

$$Depth = Max_{s \in L_{EAF}}(d(s, sink)), \tag{4.5}$$

the number of hops from the sink to the deepest leaf in the tree (the maximum number of hops towards the sink in the tree). We define the weighted length of the Path (s_1, s_k) as:

$$WPath(s_1, s_k) = \sum_{i=1}^{k-1} d(s_i), \tag{4.6}$$

the sum of the degrees of the descendant sensors. Let L'_{EAF} be all the leaves in a subtree rooted at sensor s, $s \in M$. We define the maximum weighted depth of the subtree as:

$$MaxWPath(s) = Max_{s_i \in L'_{EAF}}(WPath(s_i, s)), \tag{4.7}$$

the maximum degree of all the descendant sensors in L'_{EAF} to root to sensor s in the subtree. For all $(s \in L_{EAF})$, $MaxWPath(s) = 0$.

Finally, T_{max} be the maximum acceptable latency.

In the following Section, 4.4, we describe our ETAPT algorithm.

4.4 ETAPT description

This section is related to *[FMLE10b; FMLE11b; FLE14]*.

As shown in Figure 4.2, the tree is built out from the sink, taking into account the degree of connectivity of sensors $d(s)$. The sensors with the highest degree of connectivity are selected as parents and those with lowest degree of connectivity as leaves. Given T_{max}, ETAPT will determine the ADAPT for each parent based on its position, its number of leaves and the depth of the tree. We assume that every sensor generates a data packet of the same length periodically, and multiple packets can be combined into one packet after the data aggregation process. Any packets arriving after the ADAPT time calculation are discarded. The algorithm consists of two major procedures: $MaxWPath$, $Hop_{Distance}$, degree of sensor and average waiting and aggregation times determination.

4.4.1 $MaxWPath$ and $Hop_{Distance}$ of sensor determination

The first phase consists in determining, for each sensor in the tree, its $MaxWPath(s)$ and $Hop_{Distance}\,(s)$. The Sink broadcasts a beacon as a $RequestMaxWPath$ with a $Hop_{Distance}$ field, which is incremented as the beacon travels through the tree as shown in Figure 4.3(a). Every sensor, on receiving the $RequestMaxWPath$, adds

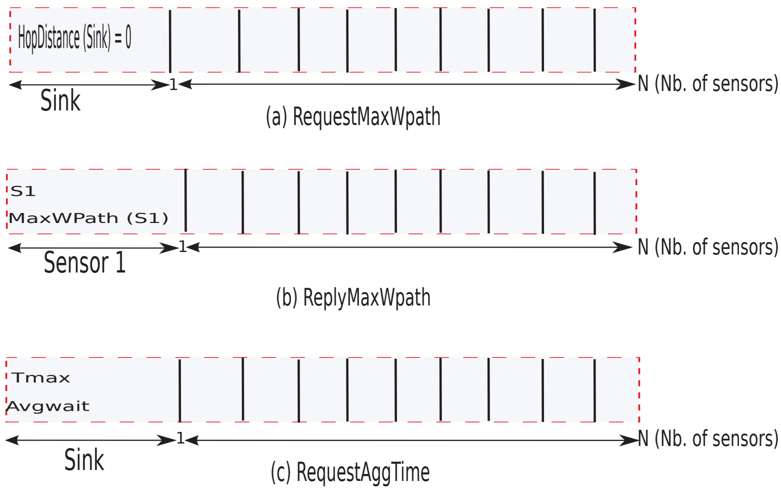

Figure 4.3: Beacon structure

its $Hop_{Distance}$ value to the beacon, and forwards it to its neighbours. In order to reply to the $RequestMaxWPath$ message, every sensor, starting from the deepest leaf, calculates its own $MaxWPath$ to its parent, generates a $ReplyMaxWPath$ message and sends it to its parent as shown in Figure 4.3(b). Suppose that $s \in M$ is a parent. It calculates and saves its own $MaxWPath$ (s) based on the $ReplyMaxWPath$ it receives, generates a new $ReplyMaxWPath$ including its own $MaxWPath$ and sends it to its parent. The $ReplyMaxWPath$ messages are propagated in a cascading manner along the tree towards the sink. When the sink has received all the $ReplyMaxWPath$ messages, it chooses the largest

$MaxWPath$ value from among them and sets:

$$MaxWPath(Sink) = Largest(MaxWPath). \tag{4.8}$$

4.4.2 Determination of average waiting and aggregation times

The second phase of ETAPT consists in determining the average waiting time Avg_{wait} per sensor in order to determine the aggregation Time Agg_{Time} in the tree. The Avg_{wait} for each sensor (s) is based on T_{max}, $MaxWPath(s)$ and $Hop_{Distance}$ (s). When the sink receives a request from an external user specifying T_{max}, the sink, based on the information it received in the first step, calculates the Avg_{wait} per sensor and Agg_{Time} in the tree as follows:

$$Avg_{wait} = \frac{(T_{max} - \delta * Depth)}{MaxWPath(sink)} \tag{4.9}$$

We assume that $T_{max} > (Depth * \delta)$. After the sink has calculated the Avg_{wait}, it broadcasts a new beacon message as shown in Figure 4.3(c) through the network including T_{max} and Avg_{wait} as shown in Figure 4.4. Every sensor, on receiving the new beacon message, calculates its Agg_{Time} as follows:

$$Agg_{Time} = Avg_{wait} * MaxWPath(s) + (Depth - Hop_{Distance}(s)) * \delta \tag{4.10}$$

δ is the minimum transmission time between two sensors of the same $Hop_{Distance}$ in the tree.

4.4.3 Illustration

Consider a simple topology consisting of 15 sensors as shown in Figure 4.5. We want to calculate $d(s)$, $Hop_{Distance}$ (s), $MaxWPath(s)$ and Agg_{Time} (s) for each sensor in the tree. We suppose that $T_{max} = 5$s and $\delta = 0.2$s. Taking into account equation (4.9), the $Avg_{wait} = 0.64$s and the Depth $= 3$. The ADAPT time

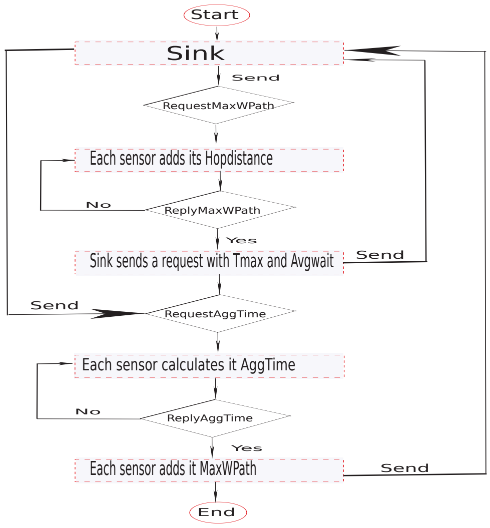

Figure 4.4: ETAPT: Algorithm

calculation is summarized in Table 4.1.

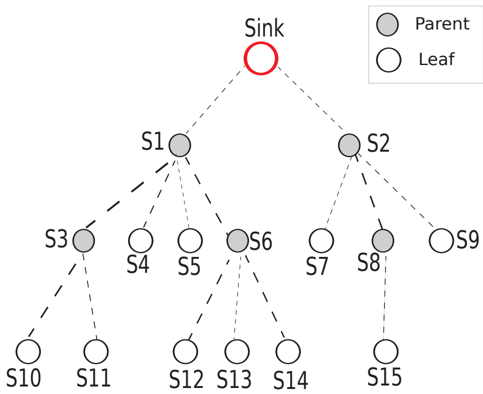

Figure 4.5: WSN: ADAPT calculation

In the following Section, 4.5, we define the performance metrics and present comparative results.

Table 4.1: ADAPT calculation

S	d (S)	$Hop_{Distance}$ (S)	$MaxWPath$ (S)	Agg_{Time} (S)
S_1	5	1	7	4.88
S_2	4	1	4	2.96
S_3	3	2	2	1.48
S_4	1	2	0	0.20
S_5	1	2	0	0.20
S_6	4	2	3	2.12
S_7	1	2	0	0.20
S_8	2	2	1	0.84
S_9	1	2	0	0.20
S_{10}	1	3	0	0
S_{11}	1	3	0	0
S_{12}	1	3	0	0
S_{13}	1	3	0	0
S_{14}	1	3	0	0
S_{15}	1	3	0	0

4.5 Performance metrics and Comparative results

4.5.1 Performance metrics

The following metrics are used to evaluate our approach:

- Data Aggregation Gain (DAG)

DAG is defined as the ratio of the benefit of traffic reduction due to aggregation to the total traffic generated without aggregation.

$$DAG = 1 - \frac{P_{Aggregated}}{\sum_{i=1}^{N} P_{Generated_i}} \tag{4.11}$$

$P_{Aggregated}$ is the total number of data packets aggregated by parents.

- Aggregation Time (Agg_{Time})

Agg_{Time} is defined as the appropriate time need by a parent to aggregate the data from its leaves.

- End-to-End Delay (E_2E_{Delay})

$Delay_{E2E}$ is the average of the time difference between sensed data leaving a sensor and it being received by the sink.

$$Delay_{E2E} = \frac{\sum_{i=1}^{P_{Received}}(T_{Received_i} - T_{Ransmission_i})}{P_{Received}} \tag{4.12}$$

$P_{Received}$ is the total number of data packets received by the sink. $T_{Received}$ is the reception time at the sink, $T_{Transmission}$ is the transmission time from each sensor. The lower the value, the more promptly is data delivered to the sink.

- Energy Consumed (EC)

Often, sensors are deployed in a hostile environment where replacing the batteries is not always possible. A good choice of energy model is essential to optimize sensor network lifetime. Our approach assumes that sensors are usually in the active mode. The energy model used is the same as in [CPH08]. For each pair of sensors (S_i, S_j), the energy consumed when sending a packet of m bits over a one-hop wireless link d can be calculated as:

Sending sensor energy consumption:

$$E_{Ti}(m, D) = E_{elec} * m + E_{amp} * m * D^2 \tag{4.13}$$

Receiving sensor energy consumption:

$$E_{Rj}(m) = E_{elec} * m \tag{4.14}$$

The total energy consumed by each pair (S_i, S_j) is:

$$E_T(m, D) = E_{Ti}(m, D) + E_{Rj}(m) \tag{4.15}$$

E_{Ti} is the energy consumed for the transmission of a packet by the source S_i, E_{Rj} is the energy consumed to receive a packet S_j, E_{elec} is the energy consumed to run the transmitter and receiver, E_{amp} is the energy used by the amplifier and D is the Euclidean distance between S_i and S_j.

4.5.1.1 Simulation set-up

We implemented a simulation of our network topology using QualNet 5.0 [Qua97] A topology is totally described by the number of stationary sensors N belonging to the network and their locations. Throughout our analysis, we deploy 100 fixed sensor nodes inside a square area L. The sink is placed at the top left corner of L. During the execution of our simulations, a given source and destination pair remains in the evaluated set until communication between them fails due to energy depletion. We repeated the experiments 20 times for the same topology, with the 95% confidence interval of each data. We took the average value of these 20 runs. Initially, each sensor was charged with an energy of 10^4 Joules. In the analysis, we set T_{max} = 3s, 4s, 5s, 6s.

The parameters of analysis are described in Table 5.2.

Table 4.2: Simulation parameters

Parameters	**Description**	**Value**
E	Full energy of sensor	10000 Joules (J)
E_{elec}	Energy of trans/receiver	50 (nJ/bit)
E_{amp}	Energy of amplifier	100 (pJ/bit)
L	Simulation area	1000m x 1000m
P_{Length}	Packet length	2 Kbits
Traffic rate	UDP traffic	4 packets/sec
MAC	MAC layer	IEEE 802.11b
T_{max}	Maximum acceptable latency	Between [3, 4, 5, 6]s
B	Bandwidth	128 (kbps)
R	Locality radius (m)	20m
N	Number of sensors	Between [20...100]

4.5.2 Comparative results

We ran simulation to compare our ETAPT strategy with ATC [CLL+06] and DASDR [ZWR+10] described in Section 4.1.1. Figure 4.6 depicts the evolution of DAG as a function of T_{max}. We can see that as T_{max} increases, the DAG increases for all the three methods. This shows that as T_{max} increases, each parent has enough time to aggregate its data efficiently. ETAPT, with an average DAG of 90%, outperforms DASDR and ATC, which give 84% and 73.5% respectively. This is because, in ETAPT, the Agg_{Time} of a leaf is proportional to $MaxWPath$ (leaf). A leaf with a small $MaxWPath$ should transmit the data quickly to its parent; only leaves having the same $MaxWPath$ value have the same Agg_{Time}. However, DASDR and ATC use a cascading time-out. This means that sensors at the same $Hop_{Distance}$ in the tree have the same Agg_{Time}, consequently increasing the amount of data loss due to congestion at intermediate parents.

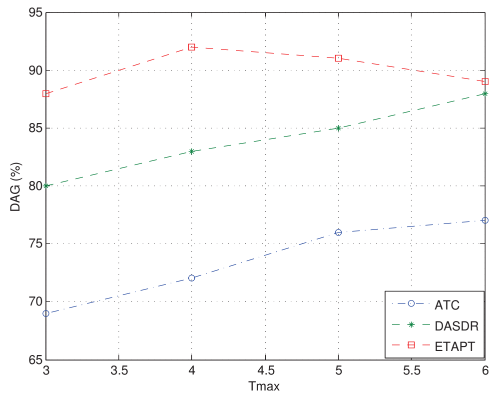

Figure 4.6: Evolution of DAG vs. T_{max}

We now evaluate the evolution of DAG as a function of the number of sensors, as shown in Figure 4.7. In the analysis, we set $T_{max} = 3$s, and we observe the evolution. We see a decreasing of DAG from $[60 - 80]$ sensors, that is due to the fact that some leaves are not disconnected to their parents resulting in a tree with disconnected sub-trees. We can see that for all algorithms, as the number of sensors increases, DAG also increases in each algorithm. That means that the three algorithms continue to deliver data accurately towards the sink as the number of sensors increases. ETAPT achieves the best DAG with an average of

86.4%, compared to 78.4% for DASDR and 71.4% for ATC.

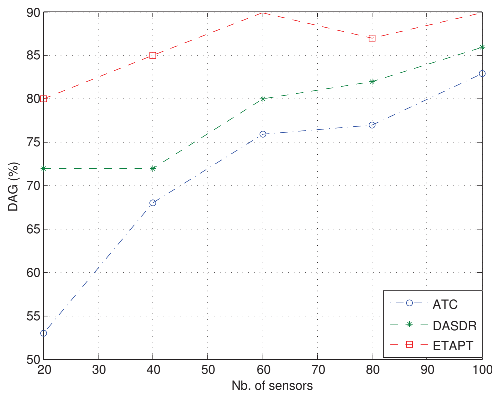

Figure 4.7: Evolution of DAG vs. Number of sensors

After a packet has been sent along a path $P_i (i = 1...., k)$, we must perform an energy reduction operation on each sensor along the path except for the sink. Thus, after a packet is sent by a sensor, the energy level of that sensor is decremented by the amount of energy required to send the data packet. A sensor is considered non-functional if its energy level reaches zero. Figure 4.8 shows the evolution of the total EC for different techniques with a varying value of T_{max}.

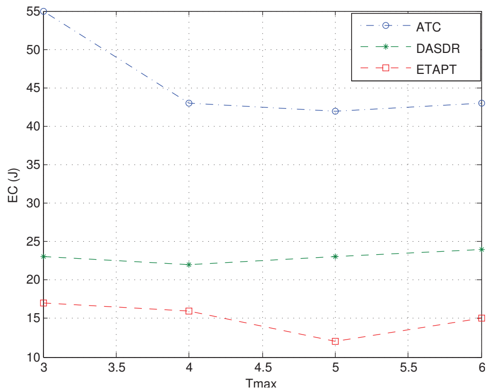

Figure 4.8: Evolution of EC vs. T_{max}

We observe that ATC and DASDR have a higher energy consumption than ETAPT. That is due to the fact that in the construction of the tree, we elect sensors having the highest degree of connectivity as parents instead of these with the highest identifier, as in ATC and DASDR. Thus, each sensor has exactly one parent that forwards its data, considerably reducing concurrent transmissions in the network. Our proposal reduces the total EC compared to DASDR and ATC by around 35% and 67% respectively.

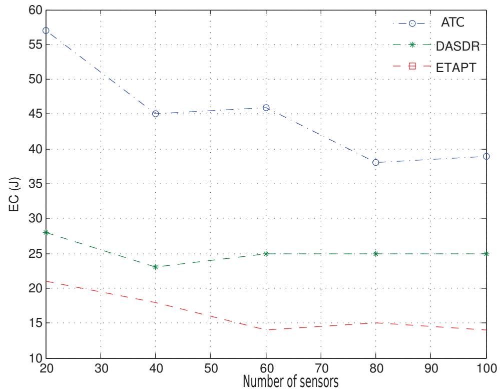

Figure 4.9: Evolution of EC vs. Number of sensors

We evaluated the evolution of the total EC with increasing number of sensors, as shown in Figure 4.9. We observe a decreasing of EC with increasing number of sensors. That is due to the fact that in dense network, parent nodes might have many leaves which helps by reducing the number of parents necessary to transmit the data in the tree, and hence reduces the EC. The average maximum energy is obtained by ATC with around 45J. An improvement is obtained by DASDR, which uses only around 25J. ETAPT outperforms both, with an average EC of just 16J.

Figure 4.10 shows Agg_{Time} vs. the locality radius. In this analysis, we set $T_{max} = 6$s, and vary the locality radius of sensors among $[20, 30, 40, 50, 60]$m. We can see that as locality radius increases, the Agg_{Time} decreases in all methods. That is because increasing the locality radius creates a disjoint network in which some sensors are not connected. This decreases the degree of connectivity of parents, and considerably reduces the Agg_{Time} of each parent. ETAPT reduces the Agg_{Time} compared to DASDR and ATC by around 31% and 60% respectively. Figure 4.11 depicts the evolution of Agg_{Time} vs. the depth of the network. We set $T_{max} = 6$s, and vary the depth of the network among $[3, 4, 5, 6]$. As we have seen

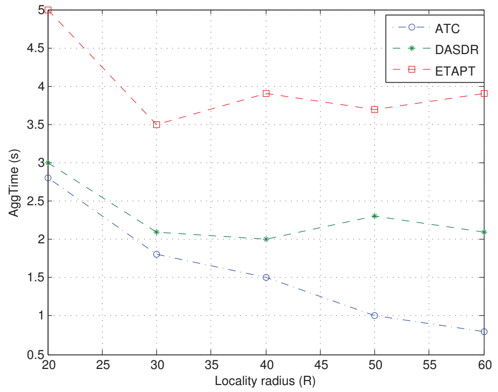

Figure 4.10: Evolution of AggTime vs. Locality radius

in Section 4.4, Agg_{Time} is a function of the depth of the network. We observe that

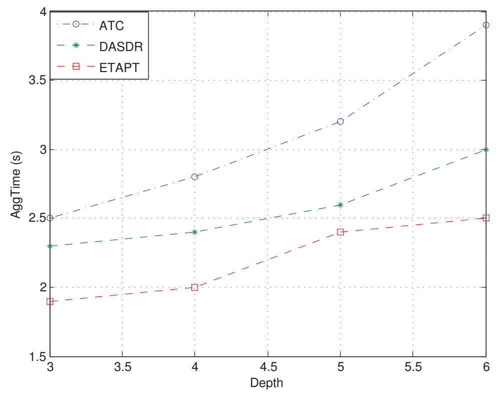

Figure 4.11: Evolution of AggTime vs. Depth

as the depth of the network increases, Agg_{Time} also increases because, the deeper the tree, the more time parents in the tree will need to aggregate the data from leaves. In all three methods, while increasing the Depth, ETAPT reduces the Agg_{Time} compared to DASDR and ATC by around 17% and 40% respectively.

Figure 4.12 depicts the evolution of $Delay_{E2E}$ vs. the degree of connectivity. We set $T_{max} = 6$s, and vary the degree of connectivity of the network among $[5, 10, 15, 20]$ with a network consisting of 200 sensors. ETAPT has a smaller $Delay_{E2E}$ compared to DASDR and ATC. This is because there is no need for each parent to synchronize with other parents in the tree before sending data.

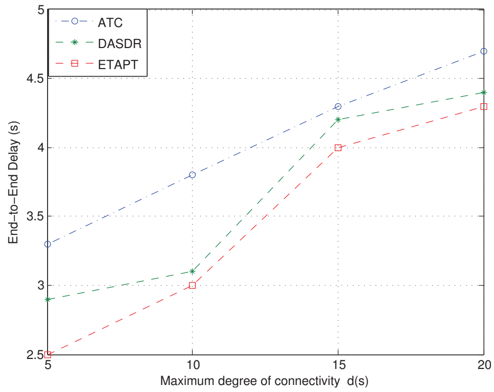

Figure 4.12: Evolution of $Delay_{E2E}$ vs. Degree of connectivity

In the following Section, 4.6, we summarize the chapter.

4.6 Summary

In this chapter, we have proposed an efficient ETAPT algorithm using the ADAPT metric. Given the maximum acceptable latency, ETAPT's calculation takes into account the position of each parent, its number of leaves and the depth of the tree, allocating an ADAPT time to parents with more leaves, so increasing the data aggregation gain and ensuring enough time to process data from leaves. Simulations were performed in order to validate ETAPT. The results obtained show that our ETAPT provides a higher data aggregation gain with lower energy consumed, Agg_{Time} and $Delay_{E2E}$ compared to the alternative DASDR and ATC methods. Our suggested ETAPT algorithm is particularly useful in resource-constrained networks, since it does not need synchronization among sensors in the network.

In the short term, we will take into account the cost of maintaining the tree in dynamic networks and evaluate the impact on energy consumption. Later, we will study the relationship between waiting time and data aggregation gain in order to make it scalable in more complex WSNs.

In Chapter 5, we propose a new and original approach by introducing into the network several mobile elements called Mini-Sinks (MSs) in order to cope with the onset of congestion due to limited storage capacity in the sensors. Multipath routing is implemented between sensors and MSs in order to distribute the global traffic over the entire network.

Chapter 5

Mobility of Mini-Sinks for Reducing Congestion

The mobility of the sink can be seen as a feasible solution to handle fixed sensors and mitigate the appearance of congestion in WSNs. In this chapter, we first present in section 5.1 our motivation and the problem addressed. Section 5.2 describes our Mini-Sink mobility for reducing congestion into the network. Section 5.3 describes the performance metrics and evaluation criteria we have used to validate our model. Section 5.4 presents simulation set-up and comparative results. Section 5.5 summarizes the chapter.

5.1 Motivation

As an emerging technology, WSNs have gained much attention in a large range of technical fields such as industrial, environmental monitoring etc. The lack of a predefined communication infrastructure increases the challenge in the design of communication techniques in hostile environments, where it is often difficult to replace sensor batteries after deployment. As all sensors collect and route the data either to other sensors or to an external entity called sink, [CT04] show that self-configuration is mandated to give all sensors the possibility of efficiently forwarding data towards the sink for improving network performance. In the most applications, sensors are assumed to be static, allowing the reporting of gathered data in a reactive manner. However, [WT09] show that the static deployment of sensors has many limitations as limited connectivity, energy, etc. Considering the limited connectivity, the deployment of static sensors may not guarantee the whole coverage of the sensing area and the overall network [KPQT05]. So, the network may be partitioned into several non-connected subnetworks. As sensors are battery-powered, some sensors may die due to the exhaustion of their batteries and may break the network connectivity. In our work, we propose to combine mobility of sensors and a controlled data aggregation approach to alleviate the limitations described above.

5.1.1 Problem definition

The main cause of decreasing network performance in WSNs is the transmission of data from all sensors towards a single sink. We have seen in Chapter 3 and 4 that, data aggregation using the tree structure could be an efficient technique for reducing the energy consumption of sensors. Let consider a WSN consisting of several sensors and a single sink as shown in Figure 5.1. Each sensor is equipped

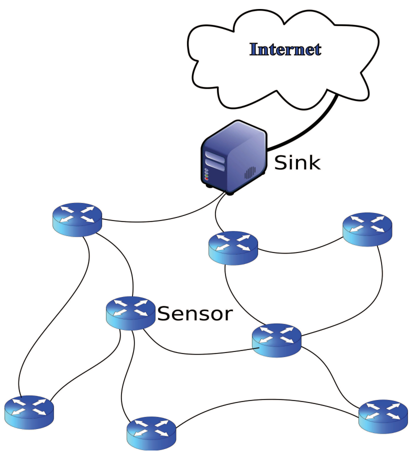

Figure 5.1: Wireless Sensor Network (WSN)

with a limited amount of storage capacity. During the transmission of data, some parents may fail to transmit or receive the data from other parents or leaves because the amount of data aggregated becomes greater than the amount of data that can be forwarded. Thus, causing the emergence of local congestion at these parents, increasing the amount of data loss. So, impacting network performances. *The problem addressed here is how to decrease the number of forwarding packets of sensors in the network?*

5.1.2 Proposition

An approach to alleviate this problem is to introduce some mobile elements in the WSN to enhance its limitations as described by [WT09]. In our approach, instead of having a central sink responsible for aggregating all the data, we introduce an original approach combining a multipath routing and the mobility of Mini-Sinks (MSs) as shown in Figure 5.2.

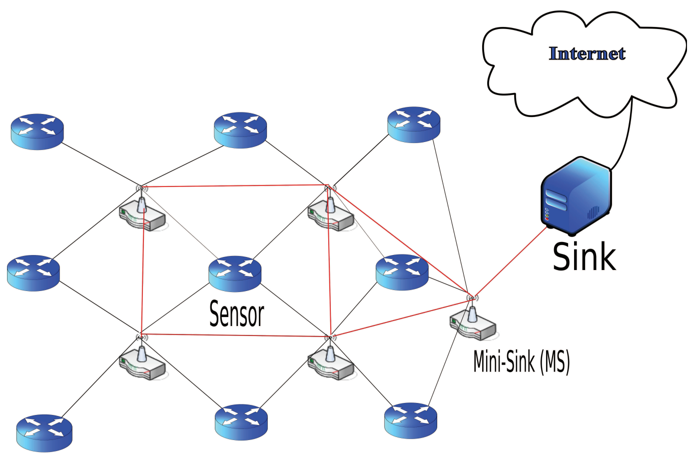

Figure 5.2: Wireless Sensor Network with Mini-Sinks

These MSs move in the sensor field according to a random mobility model in order to maintain a fully-connected network topology, aggregating the data within their coverage areas based on the Multipath Energy Conserving Routing Protocol (MECRP) and forwarding it towards the sink. MECRP is implemented in MSs and sensors in order to optimize the transmission cost of the forwarding scheme. A set of multiple paths between MSs and sensors is generated to distribute the global traffic over the entire network.

The mobility of MSs help to increase the connectivity capability, so relaxing the requirement on network connectivity between sensors. The transmission of data from sensors to MSs is done through a single hop in order to reduce the appearance of congestion into the network.

In the following Section, 5.2, we present the network model and describe Mini-Sink model.

5.2 Model description

This section is related to [FMLE10a; FMLE11c; FLE12b; FLE12a; FLE12d].

5.2.1 Assumptions

We assume in our model that:

- Sensors and MSs are deployed in an area of size L.
- Each sensor maintains a list of the identities (Id) of its MSs.
- Each sensor has its own Routing Table (RT).
- Each sensor has a limited buffer to accommodate locally gathered data.
- Each sensor takes readings and forwards them to the most easily accessible MS.
- MSs are mobile and have an unlimited energy.
- MSs know the location of all fixed sensors.
- Each MS knows its relative distance to the sink.
- Each MS floods periodically a beacon to all sensors in its locality.
- MSs are responsible for aggregating the data from sensors and forwarding it towards the sink.

5.2.2 Network architecture

Our network architecture consists of three classes of nodes:

- MSs are special nodes equipped with unlimited energy and storage capacity.
- Sensor nodes are responsible for sensing their nearby environment.
- A single sink is the final recipient of all the sensed data, and provides a gateway to conventional computing equipment.

5.2.3 Network topology

The proposed WSN can be modelled as a connected graph $G = (S, E)$, where S is the set of n stationary sensors, and each $E \subset S \times S$ is the set of links. We use the locality model suggested by [ZCD97] to determine network connectivity. The probability of a link between two sensor nodes S_i and S_j is given by:

$$P = \begin{cases} 1 \ if \ D(S_i, S_j) \leqslant R \\ 0 \ if \ D(S_i, S_j) > R \end{cases} \tag{5.1}$$

Where $D(S_i, S_j)$ is the Euclidean distance between sensors S_i and S_j, and R is the locality radius. The goal of our model is to study overall network performance resulting from the mobility of MSs. We use the terms multiple paths and route diversity interchangeably.

5.2.4 Mini-Sink mobility model

In our approach, the MSs move according to a random mobility model inside the sensor field as shown in Figure 5.3. N MSs are randomly placed in the area of size L. Each MS N_i is defined in respect of its coordinates (x_i, y_i), and moves from a given position (x_i, y_i) to a new position (xd_i, yd_i) with a velocity $[v_{min}, v_{max}]$, in the range $[0...2\pi]$. Figure 5.3 shows that each MS moves with a different velocity represented by differing dashed line styles. When a MS reaches the locality radius of the sink, it stays there for a time t_i selected in the range $[t_{min}..., t_{max}]$, in order

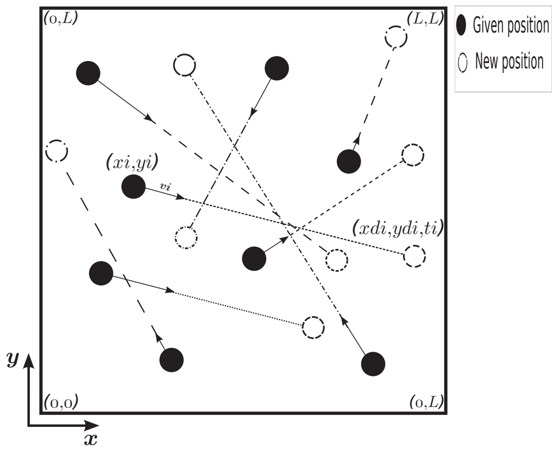

Figure 5.3: Random mobility of MSs in a square area of size L

to forward the data that it has aggregated based on the MECRP towards the sink. After this interval, the MS restarts its displacement process by selecting a new position, and so on. During mobility, when each MS arrives at the locality radius of the sink, it stays at the same position for a time t_i, which is as long as is necessary to transfer the data that it has aggregated to the sink. During this time, the MS also plays the role of a relay point for its neighboring MSs. The time needed for each MS depends on the amount of data to be transfered to the sink.

5.2.5 Multipath Energy Conserving Routing Protocol (MECRP)

In the following Section, we outline our Multipath Energy Conserving Routing Protocol.

The MECRP protocol has been designed to optimize the cost of the forwarding scheme, postpone the onset of congestion and to counteract the high traffic variability in WSNs as described by [PD07]. The route discovery approach derives directly from the Dijkstra's algorithm. [MG94] present the Meta Dijkstra's algorithm, consisting of iterative applications of Dijkstra's algorithm in a changing topology. Once a path is discovered, its links are deleted from the topology and the performance of the new shortest path in the current graph is evaluated, and so on until a set of maximal paths is found. Unfortunately, such deletion may be too restrictive as it can reject the neighbourhood of the source node from the remaining topology. [TTAE09; LMWT11; YBO09] say that it can lead to create a disconnected graph in which the source and destination nodes are not connected together. In our new approach, we prefer changing the current topology by adding limited weights to all discovered shortest path edges. We recall that the Meta Dijkstra algorithm corresponds to a particular case of the modified Dijkstra's algorithm where infinite weights are used.

In the following Section, 5.2.6, we describe the multiple paths extraction and controlled data aggregation of MSs.

5.2.6 Multiple paths extraction

We consider a network of n identical static sensors. The sink is located at several hops from the sensors. We want to extract a set of multiple paths that allows each sensor to transmit its data to the MS. Since data transmission is a function of the distance and energy, our challenge is take into account simultaneously both the Euclidean distance between sensor and MS and the current energy of the sensor. The following notations as shown in Table 5.2.6 are used in the paths calculation.

n	Number of sensors
S_i	Sensor i
C_i	Cost of S_i
C_{MS_j}	Cost of MS_j
D_{ij}	Euclidean distance between S_i and MS_j
P_i	Path from S_i to MS
e_i	Current energy of S_i
Id_i	Identity of MS_i
L	Square area where sensors are deployed
γ, δ	Weights

Table 5.1: Notations

Let $J(S_i,\ MS_j)$ be the transmission cost between S_i and $MS_j (i \neq j)$. We have modified Dijkstra's algorithm in order to compute and build the lowest cost path between a sensor and MS. This cost is a linear function of two metrics: the Euclidean distance between neighbor nodes and their current energy, defined as:

$$J(S_i, MS_j) = \gamma \frac{D_{ij}}{R} + \delta \frac{e_i}{E} \tag{5.2}$$

E corresponds to the full-charged energy of a sensor. γ and δ are weights used to change the importance of the two metrics in path cost calculation. We have used $\gamma = 1$ and $\delta = 1$, so the contributions of energy and distance are equal. Initially, we set the cost of all sensors to infinity (∞), and the cost of the MS (C_{MS}) to 0. During the mobility of MSs, each MS floods a request intended to all the sensors in it locality radius. The request contains its cost C_{MS}. For a transmission between S_i and MS_j, the algorithm:

- Selects the sensor S_i,
- compares the costs for all outgoing links (i, j),
- Updates the cost.

The following cases are checked:

- If $C_{MS_j} + J(S_i, MS_j) > C_i$, then S_i just discards the message without updates.
- If $C_{MS_j} + J(S_i, MS_j) < C_i$, the algorithm updates the cost C_i to $C_{MS_j} + J(S_i, MS_j)$. The sensor S_i records the Id j of MS_j in its routing table to further transmit the data.
- If $C_{MS_j} + J(S_i, MS_j) = C_j$, then S_i randomly chooses the cost of all outgoing links.

5.2.7 Controlled data aggregation

Consider the network topology as shown in Figure 5.4. MSs are represented by black disks with a velocity vector that points to their destination. Sensor nodes are represented by white disks. Arrow length is proportional to the velocity.

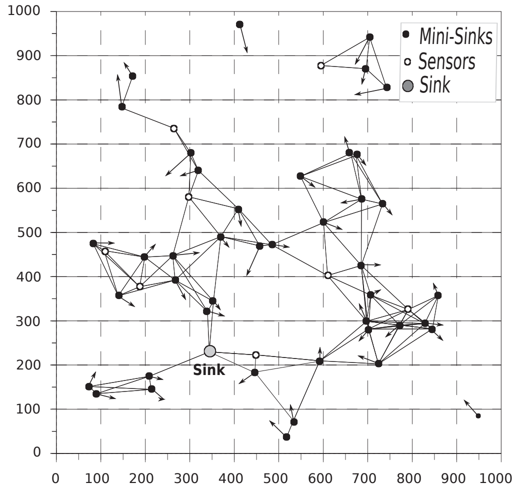

Figure 5.4: Controlled data aggregation of MSs

While each MS is moving, it broadcasts periodically a beacon to all sensors in its locality radius in order to inform them that it is a MS. The beacon contains the cost C_{MS}, which is initialized to 0, the identity Id of the MS and the type of gathered data. During the sensing activity of sensors, it may happen that some sensors are connected to many MSs due to their mobility. In order to know which MS is most suitable and presents the lowest cost path for transferring the data, each sensor in direct communication with MSs calculates the lowest cost path using MECRP described above before sending the data to the best MS as described in Section 5.2.9. Thus, for a transmission between sensors and MSs, the defined traffic is not all carried on a single path, but it is spread over multiple paths. This results in a fair balancing of the energy depletion among sensors. The onset of the global congestion is delayed, as the route diversity modifies the probability of taking a path according to its load. This dynamic path selection implies that the traffic remains more regular for the sensors involved in the routing paths. Thus, route diversity appears to be a promising solution for coping with high traffic variability and improving network performance.

We consider in our model three communication modes while MSs are moving:

- Multi-MS mode: each sensor is allowed to connect itself simultaneously to several MSs in order to increase its connectivity capabilities. The sensor node under consideration stores and updates the lowest cost path towards each accessible MS.

- Multiple routing paths MS mode: each sensor is only interested in the closest MS, although multiple paths are used between a sensor and the closest MSs. These paths are discovered using MECRP.
- MS Point-to-point mode: two MSs want to establish a connection with each other. In this mode, packets always follow a single path if the topology stays stable. However, the path is updated when the topology change occurs.

5.2.8 Energy model

In our model, sensors use batteries as their source of energy. The good choice of energy model is essential to maximize sensor lifetime. Our model considers that sensors are in the active mode. The energy model used is the same as in [CPH08], and the same as in Chapter 4, Section 4.5. We recall that the reception energy is not taken into account in our approach as the transmission between sensors and MS is done via a single hop.

5.2.9 Illustration

Let consider the network topology consisting of 9 sensors, 5 MSs and a single sink and as shown in Figure 5.5. Let consider the transmission from S_2 to the sink via MS_1 and MS_2. In this case, we have two possible cases.

Considering S_2 and MS_1:

- If $C_{MS_1} + J(S_2, MS_1) < C_2$, then S_2 updates its cost and adds the Id of MS_1 in it routing table as a possible MS to further transmit the data.
- If $C_{MS_1} + J(S_2, MS_1) > C_2$, the S_2 does not update it cost.

Considering S_2 and MS_2:

- If $C_{MS_2} + J(S_2, MS_2) < C_2$, then S_2 updates it cost adds the Id of MS_2 in it routing table.

- If $C_{MS_2} + J(S_2, MS_2) > C_2$, then S_2 does not update it cost.

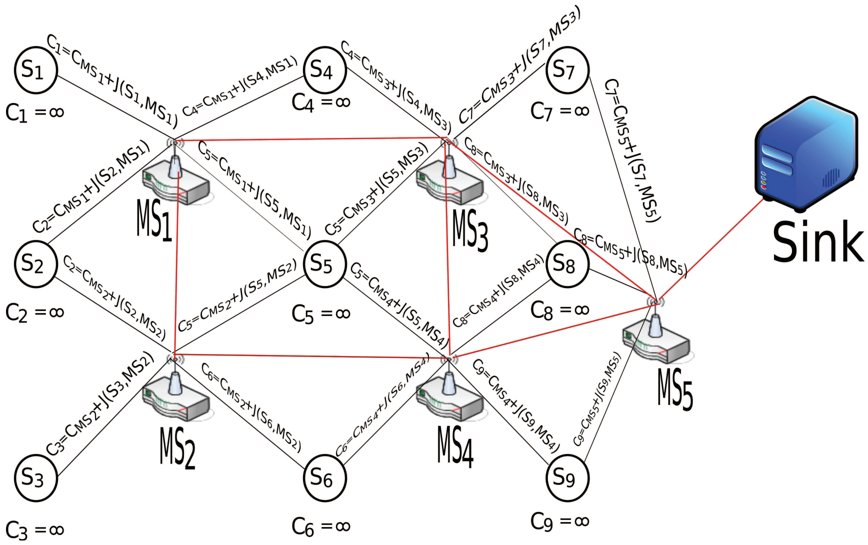

Figure 5.5: Multipath discovery calculation

At the end, each sensor in the network knows the cost of the path of all the direct MSs and the corresponding Ids. All the discovered paths are classified in the routing table (see Algorithm 4). We number each discovered path P_i for $i = 1...q$ such that $C_{P_1} < C_{P_2} < C_{P_3}...C_{P_i}...C_{P_q}$. C_{P_i} represents the cost of the path i. Whenever S_2 want to transmit the data, several possible paths can be used to forward the data. In conventional data transmission based on a single path, for each transmission, S_2 generally chooses the path P_1 because it has the lowest cost. The other paths are considered as alternatives. In our new approach, S_2 uses each discovered path in turn for the transmission of successive connection packets. The same calculation can be performed for all the sensors in the network.

In the following Section, 5.3, we describe the performance metrics and evaluation criteria that we used to validate our model.

procedure INITIALIZATION;
    $C_s = 0$; $C_i = \infty$ for all $i = 1...N$;
    $e = \infty$; R =50; L=1000; E=10000;
end procedure;
procedure MULTIPLE PATHS EXTRACTION;
    for $i = 1..N$ **do**;
        if $C_i + J(i, j) < C_j$ **then**;
            $C_j \leftarrow C_i + J(i, j)$;
            (Update RT);
            $S_j \leftarrow Id$;
        else;
            $C_i > C_j$;
            (No update, discard);
        end if;
    end for;
end procedure;
procedure CONTROLLED DATA AGGREGATION;
    Queue Initialization(Q);
    for $i = 1..N$ **do**;
        $C_i = \infty$;$C_s = 0$;
        while (Q != Null) **do**;
            Queue Removal(Q, i);
            if $C_j > C_i + J(i, j)$ **then**;
                $C_j \leftarrow C_i + J(i, j)$;
                Queue Insertion(Q, j);
            end if;
        end while;
    end for;
end procedure;

Algorithm 4: MECRP: Pseudo-code

5.3 Performance metrics and Evaluation criteria

5.3.1 Performance metrics

The following metrics are used to evaluate our approach:

- Packet Delivery Ratio (PDR)

PDR is the ratio of packets that are received by the sink to the total packets generated by sensors.

$$PDR = \frac{P_{Received} * 100}{\sum_{i=1}^{n} P_{Generated_i}} \tag{5.3}$$

$P_{Received}$ is the total number of data packets received by the sink, $P_{Generated}$ the total number of data packets generated by sensors, and n the number of sensors.

- Throughput

Throughput is the total number of data packets received by the sink in a period of time.

$$Throughput = \frac{\sum_{i=1}^{n} P_{Received_i} * P_{Length}}{SIMU_{Time}} \tag{5.4}$$

$P_{Received}$ is the total number of data packets received by the sink, P_{Length} the length of a packet, $SIMU_{Time}$ the simulation time.

- End-to-End Delay (E_2E_{Delay})

E_2E_{Delay} is the average sum of the difference delay of each data packet is received by the sink and the time a data packet is sent by sensors to MSs.

$$E_2E_{Delay} = \frac{\sum_{i=1}^{P_{Received}} (T_{Received_i} - T_{Ransmission_i})}{P_{Received}} \tag{5.5}$$

$T_{Received}$ is the reception time by the sink, $T_{Ransmission}$ the transmission time by each sensor. Smallest is this value indicates the promptness of data delivered to the sink.

- Multiple Paths Overhead (MPO)

We have seen in subsection 5.2.7 that, while each MS is moving, it broadcasts a beacon message to all sensors in its locality radius in order to inform them that it is a MS. We consider in our model that, the beacon message exchanged to find the routing paths is a data packet. We evaluate the MPO per sensor due to discover, establish, update and maintain multiple routing paths between sensors and MSs. MPO is the percentage of the total number of packets exchanged (to calculate, update and maintain multiple paths by a each sensor) to the total number of packets that are received by the sink.

$$MPO = \frac{\sum_{i=1}^{n} P_{Exchanged_i} * 100}{P_{Received}} \tag{5.6}$$

$P_{Exchanged}$ is the total number of packets exchanged by sensors.

- Residual Energy (RE)

When a packet is sent along a path $P_i (i = 1...., q)$, we must perform an energy decrease operation on sensor except for the MS. Thus, after a data packet is sent by a sensor, the energy level of that sensor is decremented by the amount of energy required to send the data packet as described in 5.2.8. Thus, the RE of a sensor is a fraction of its initial energy value. RE is the difference between the initial energy and the energy consumed by a sensor:

$$RE = E - E_T(k, D) \tag{5.7}$$

- Energy Overhead (EO)

EO is the ratio of the total energy exchanged (to discover, establish, update and maintain multiple paths) to the total energy consumed to transfer the data by each sensor to MSs.

$$EO = \frac{\sum_{i=1}^{n} E_{Exchanged_i} * 100}{E_T(k, D)} \tag{5.8}$$

$E_{Exchanged}$ to calculate, maintain multiple paths.

- Network Lifetime (NL)

NL is calculated as the total number of packets that can be transferred in the network before the link between sensors and MSs is disconnected due to the energy depletion. We have seen above that when a packet is sent along a path $P_i(i = 1...., q)$, we must perform an energy decrease operation on sensor except for the MS. If after the decrease operation, RE of a sensor becomes 0, the sensor under consideration and its corresponding links are removed from the topology. Suppose that $P(S_i, MS)$ is the path between a given sensor S_i and a destination MS. NL is obtained by maximizing the RE of the path $P(S_i, MS)$.

$$NL = max \sum_{i=1}^{q} RE(P(S_i, MS)) \tag{5.9}$$

5.3.2 Evaluation criteria

For the defined network topology, MECRP is applied between a selected sensor and the closest MS. We recall that in the case of a single sink and the mobile sink as described by [IKN06], a single packet is transmitted between each pair (S_i, S_j). In our approach, as multiple paths are used between sensors and MSs, we assume that many packets are transmitted between each pair (S_i, MS_j). As a consequence, packets can be transmitted over multiple paths until the network topology changes to a new configuration. We used simulations to investigate:

- How many MSs should be used in order to have a fully-connected network?
- The PDR and Throughput due to the use of MSs.
- The effect of session length (k) on overall NL and RE.
- The effect of locality radius (R) on overall NL and RE.
- The effect of network density on overall NL and RE.
- The EO and MPO due to calculate and maintain multiple routing paths.
- The E_2E_{Delay} due to the mobility of MSs.

In the following Section, 5.4, we describe the simulation set-up and present the comparative results.

5.4 Simulation set-up and Comparison results

5.4.1 Simulation set-up

We implemented a simulation of our network topology using QualNet 5.0 [Qua97]. A topology is totally described by the number of stationary sensor nodes n belonging to the network, their locations, and the link characteristics (l direct edges between sensor nodes). A link is defined by a starting node (head) and a finishing node (tail). The parameters of analysis are described in Table 5.2.

Parameters	**Description**	**Value**
E	Full Energy of Sensor	10^4 (J)
E_{elec}	Energy to run transc/receiver	50 nJ/bit
E_{amp}	Energy of amplifier	100 (pJ/bits)
L	Simulation area (m)	1000 x 1000
Packet	Packet length	2 Kbits
Traffic	UDP traffic rate	6 packets/sec
MAC	MAC layer	IEEE 802.11b
S_{length}	Session length	[1...60] packets
B	Bandwidth	250 (kbps)
R	Locality Radius	50m
Movement	Random Way Point model	
Routing	Routing protocol	MECRP
v_{max}	Maximum velocity	10mps
$SIMU_{Time}$	Simulation time	1000s
t_i	Time Needed	[0...3]s
n	Number of Sensors	[25...100]
N	Mini-Sinks	30

Table 5.2: Simulation parameters

In all our analysis, we deploy 100 fixed sensors inside a square area of seize L.

The sink is placed at the corner of the square area. Each sensor is able to transmit to its lowest cost MS a certain number of packets before its energy is depleted. MSs move with a velocity in the range [0.... v_{max}]. During the execution of our simulations, a given source and destination pair remains in the evaluated set until communication between them fails due to energy depletion. We repeated 10 times the experiments for the same topology, with 95% confidence interval. We took the average value of these 10 runs. Initially, each sensor is charged with an energy of 10^4 Joules. A sensor node was considered non-functional if its energy reached the value 0.

5.4.2 Comparison results

All the results are compared with the case of a single and mobile sink as presented by [IKN06]. [IKN06] use random sink mobility to reduce data latency and increase the network lifetime of WSNs. A single sink is moving in a random manner in the sensor field to aggregate the data. The restriction in their approach is that the mobile sink can only gather data from 3 hop neighbors. However, random data collection does not guarantee the collection of data from all sensors and may result in long delays.

5.4.2.1 Multi-MS mode

- Number of MSs needed

Figure 5.6 shows the results of the number of sensors connected simultaneously to several MSs in order to increase the connectivity capability. We can see that the number of sensors connected to MSs increases as the number of MSs increases. The fully-connected network can be achieved using more than 25 MSs for a network consisting of 100 sensors.

5.4.2.2 Multiple routing paths MS mode

- Evolution of PDR due to the use of MSs

Figure 5.7 shows the results of PDR as a function of number of sensors. We observe that, we obtain the same PDR as [IKN06] with 25 sensors. When

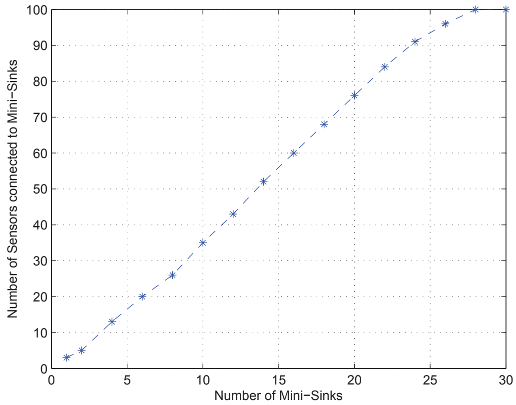

Figure 5.6: Number of sensors connected to MSs

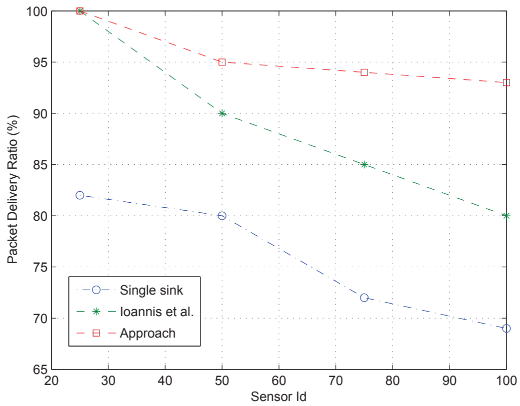

Figure 5.7: PDR vs Number of sensors

the number of sensors varies between [25...100], the single static sink presents a small percentage of PDR. That is due to the fact that, in the single sink, the forwarding is done using intermediate sensors and some sensors may fail to receive of transmit the data. Hence, [IKN06] achieve a higher PDR than the case of a single static sink. Because with [IKN06], the mobility of the sink reduces the use of intermediate sensors during the forwarding schemes. In all cases, our MS approach achieves the better PDR with an average of 95.5%, compared to 88.55% for [IKN06] and 75.75% for the single static sink. That is due to the fact that in our approach, the forwarding is made from sensors to MSs, no transmission between intermediate sensors.

- Evolution of Throughput due to the use of MSs

Figure 5.8 shows the results of throughput as a function of the velocity of MSs. We recall that the throughput depends on the velocity of MSs. It can be observed from Figure 5.8 that, the throughput decreases with increase velocity of MSs. We can see that the maximum throughput is achieved with the velocity

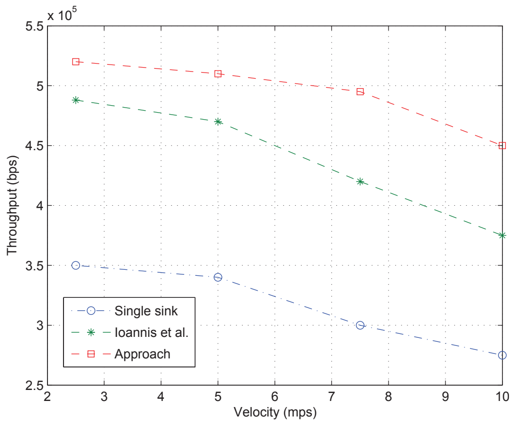

Figure 5.8: Throughput vs Velocity

of 2.5mps. When the velocity increases from [2.5 - 10]mps, our approach outperforms [IKN06] and the single sink with an average of 11.24% and 35.94% respectively. That is due to the fact that [IKN06], only a single static sink is moving, compared to our approach in which many MSs are moving. We can conclude that, increasing the velocity of MSs degrades the throughput since some sensors may not be able to transfer the data to MSs on time.

- Effect of session length (k) on overall NL.

We evaluate now the overall NL. In the single and mobile sink as described by [IKN06], a single packet is transmitted in Session Length (S_{length}) between each pair (S_i, S_j). We assume that k packets are transmitted in each S_{length} between each pair (S_i, MS_j). We then vary the value of k in order to observe the behavior of our approach and the techniques implemented.

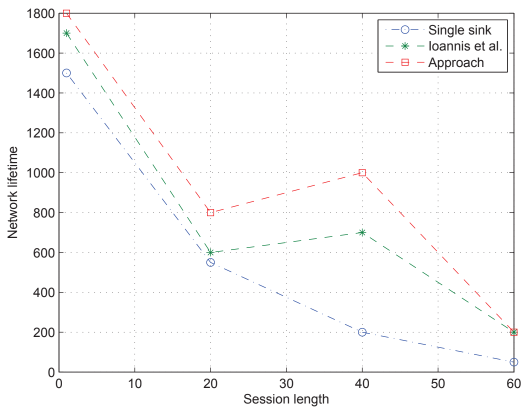

Figure 5.9: Network lifetime vs Session length

Figure 5.9 shows the results of NL as a function of S_{length}. We send k packets at a time for each S_{length}. We observe from Figure 5.9 that, when we vary S_{length} between [1...60], [IKN06] achieve better NL than the case of a single static sink. In all cases, our Mini-Sink approach outperforms [IKN06] by around 16% and the single static sink by around 40% due to the use of multipath during the forwarding.

- Effect of locality radius (R) on overall NL.

Figure 5.10 shows the impact of the locality radius on NL. We can see that when the locality radius is less or equal to 35m, the single static sink improves

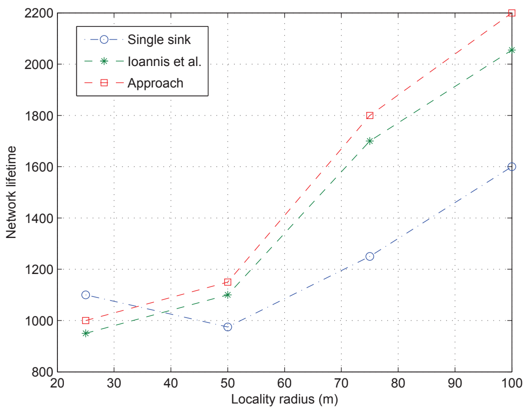

Figure 5.10: Network lifetime vs. Locality radius

NL than [IKN06] and our approach by around 14% and 5% respectively. While, when the locality radius varies between [40...100]m, our approach significantly outperforms [IKN06] and the single static sink by around 5% and 20% respectively. That is due to the fact that increasing the locality radius may create a disconnected network in which some nodes are not connected together. In contrast, in our case, the mobile MSs help to maintain the connectivity between sensors and MSs in order to transmit the data at any moment.

- Effect of RE on S_{length}.

Figure 5.11 shows the results of the RE vs. S_{length}. We see that in all the three algorithms, RE increases with increasing S_{length}. That is due to the fact that we do not take into account the reception energy as in our approach, each sensor send its data to MS via a single hop. In comparison with the case of a single sink and [IKN06], in which multihop is used, the consideration of reception energy could affect the evolution of RE presented here. In the case of a single static sink, the forwarding scheme uses multi-hop along the shortest path towards the sink. We observe that [IKN06] improve RE than the single static sink by around 20%. Our approach still outperforms [IKN06] in terms of RE by around 15% and the single static sink by around 31%.

- Evolution of RE on Locality radius.

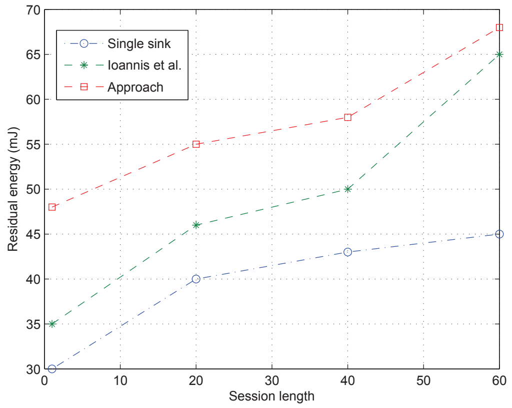

Figure 5.11: Residual energy vs Session length

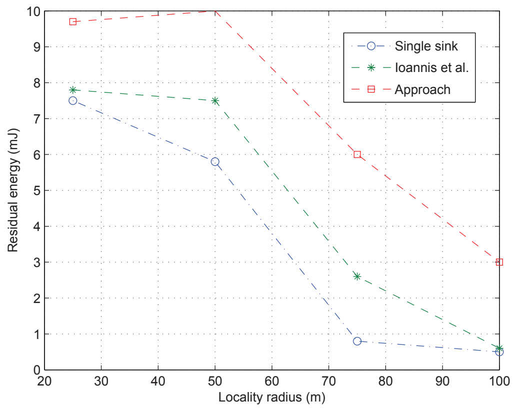

Figure 5.12: Residual energy vs. Locality radius

Figure 5.12 depicts the impact of the locality radius on RE. We see that, as the locality radius varies between [25...100]m, the RE of all the three techniques decreases considerably. That means the locality radius has a strong impact on the RE. In all the cases, our approach outperforms [IKN06] and the single static sink by around 36% and 50% respectively.

- Evolution of NL as a function of RE and network density.

In order to understand the behavior of our approach, we evaluate our algorithm between [100...300] sensors. Figure 5.13 and Figure 5.14 depict the average NL and RE as a function of network density. We observe that, when we increase the number of sensors by keeping the locality radius constant, the results obtained by [IKN06] are very close to our approach in terms of NL as shown in Figure 5.13. [IKN06] perform better than the case of a single static sink. In terms of the maximal RE as shown in Figure 5.14, our approach still outperforms [IKN06] and the single static sink by around 45% and 63% respectively.

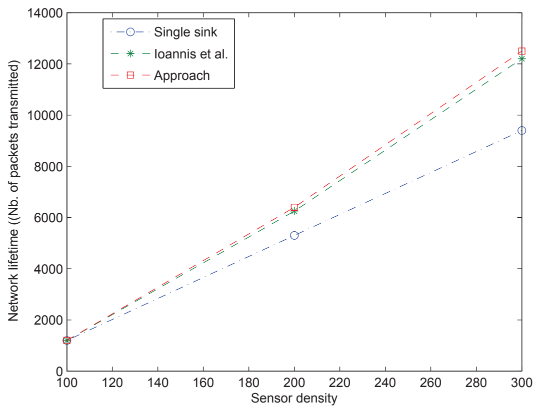

Figure 5.13: Network lifetime vs. Network density

- Evolution of EO and MPO

Figure 5.15 and Figure 5.16 show the evolution of EO and MPO as a function of number of sensors. We can see from Figure 5.15 that, our approach performs

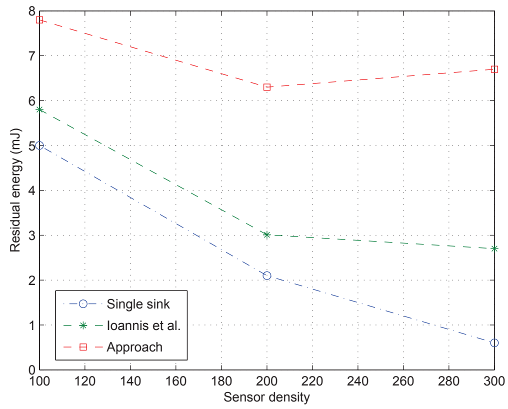

Figure 5.14: Residual energy vs. Network density

better [IKN06] and the single sink in terms of the maximum EO by each sensor with around 11%, 20% and 35% respectively. For the average EO, our approach presents an average EO with around 7.75%, [IKN06] around 12.25% and the single sink around 21.75%. Statistically, our approach outperforms [IKN06] and the single sink with around 58% and 180% respectively.

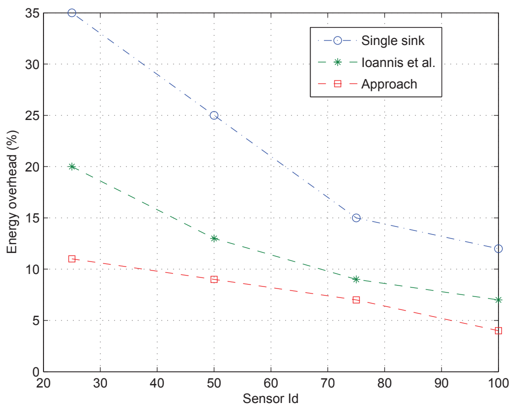

Figure 5.15: Energy overhead vs. Number of sensors

In Figure 5.16, we observe that our approach and [IKN06] used the lowest beacon packets to find the routing paths compared to the single static sink. That is due to the fact that the single static sink uses the simple flooding in the route discovery process, and needs a higher number of beacon messages if the battery fails. Our approach improves MPO than [IKN06] and the single sink with an

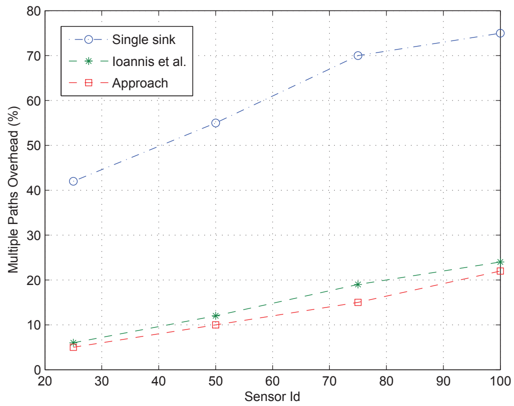

Figure 5.16: Multiple Paths Overhead vs. Number of sensors

average of around 14.75% and 78.51% respectively. This happens because our approach needs less beacon messages to discover and maintain multiple routing paths to MSs.

5.4.2.3 MS Point-to-point mode

- Evolution of E_2E_{Delay}.

Figure 5.17 shows the normalized E_2E_{Delay} as a function of the velocity of MSs. We can see that the single static sink presents the large E_2E_{Delay}. Because, whenever a sensor wants to send the data, a sensor performs a route discovery process which takes more time. Compared to the single static sink because in [IKN06], the mobility of the sink reduces considerably the route discovery process and so on. Whereas, in the single static sink, there is no mobility of the sink. Figure 5.17 shows that with the increasing velocity of MSs, our approach achieves the smallest E_2E_{Delay} than [IKN06] and the single static sink.

In the following Section, 5.5, we summarize the chapter.

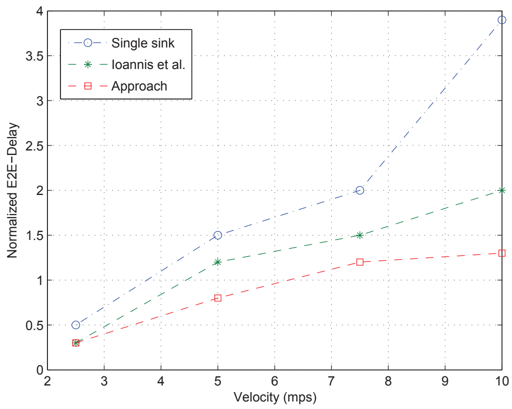

Figure 5.17: E_2E_{Delay} vs. Velocity

5.5 Summary

In this chapter, we have seen the use of many MSs, instead of a single sink for aggregating data. Many mobile MSs move according to a random mobility model inside the sensor field in order to aggregate data within their coverage areas based on the controlled MECRP and forward it towards the sink. MECRP, based on route diversity, is implemented in MSs and sensors in order to optimize the transmission cost of the forwarding scheme. Thus, a set of multiple paths between MSs and sensors is generated to distribute the global traffic, so as to reduce the appearance of congestion over the entire network. We have compared the results obtained with those for a single and mobile sink proposed by [IKN06], and showed that our solution can achieve better results in terms of PDR, Throughput, E_2E_{Delay}, NL, RE, EO and MPO. The mobile MSs help to increase the connectivity capability, so relaxing the requirement on network connectivity between sensors. The transmission of data from sensors to MSs is done through a single hop in order to reduce the appearance of congestion in the network.

In our future work, we will evaluate the impact of interference between sensors and MSs during the forwarding procedures, and study the complexity of our proposed method.

In the following Chapter 6, we propose a multi-channel assignment in multi-radio to reduce network interference, and thus improve network performance.

Chapter 6

Multi-Channel Assignment in Multi-Radio

Sensors may use many radio interfaces sharing a single wireless channel, which they may use to communicate with several neighbours. Two sensors operating on the same wireless channel may interfere with each other during the transmission of data. In this chapter, we present in section 6.1 our motivation. Section 6.2 states the problem and presents our proposition. Section 6.3 describes our distributed channel assignment for reducing interference. Section 6.4 describes performance metrics and evaluation criteria. Section 6.5 presents performance and comparative results and Section 6.6 summarizes the chapter.

6.1 Motivation

In our Chapter 3 and 4, we have proposed a tree-based data aggregation, in which the aggregated data are propagated from parent to parent towards the sink in order to reduce the amount of data transmitted. Sensors may embody many radio interfaces sharing a single wireless channel, which they may use to communicate with several neighbours. During the transmission of aggregated data, an efficient allocation of channels could reduce interference. [LÓ7] shows that, computing the minimum number of channels necessary to assign to all sensor nodes in the network is NP-Hard. We propose a distributed method called: Well-Connected Dominating Set Channel Assignment (WCDS-CA), in which we assign a unique channel in the network to each radio interface in such a way that the number of distinct channels assigned to adjacent links of any given sensor is at most the number of radio interfaces of that sensor.

6.2 Problem statement and Proposition

6.2.1 Network topology and Assumptions

The proposed WSN can be modelled as a connected graph $G = (S, E)$, where S is the set of N fixed sensors, where each sensor node may be equipped with many radio interfaces and $E \subset S \times S$ is the set of M wireless links between any two sensor nodes. Two sensors S_i and S_j with $(i, j) \in E$ can communicate if the Euclidean distance between both $D(S_i, S_j) \leqslant R$, and both have a radio interface with a common channel (R is the locality radius). Let $v \in S$, and $\mathrm{d}(v)$ the set of adjacents neighbours of v.

Our network architecture consists of three classes of nodes:

- Leaves are sensors with the lowest degree of connectivity.
- Parent are sensors with the highest degree of connectivity.
- Mediators are sensors linking two adjacent parents.

In our approach, we make the following assumptions:

- Sensors are deployed in an area of size L.
- Radio interfaces in each sensor have the same reception and transmission range.
- Each sensor maintains a list of the identifies (Ids) of its neighbours.

- Each sensor keeps track of its own degree of connectivity value.
- Sensors are homogeneous (same computing, memory,...) and fixed.
- Each leaf node has one parent that is responsible for forwarding the received data towards the sink.
- Leaves can only sense and transmit their measurements to their parents.
- Multiple packets can be combined into one packet after aggregation process.
- A single sink is the final recipient of all the sensed data.

6.2.2 Problem statement

We define a channel assignment matrix X: $E \longrightarrow C$, such that for all pairs of sensor nodes u and v adjacent (u,v) $\in E$, X(u) $\neq$ X(v). $C = \{1, 2....k\}$, a set of positive integers represents the available channels. Sensors may incorporate many radio interfaces sharing a single wireless channel, which they may use to communicate with several neighbours. Data transmission along a communication link between two adjacent parents may interfere with transmissions along other communication links if they transmit on the same channel. Two adjacent parents communicating with links (i, j) and (i', j') interfere if they transmit on the same channel at the same time. Thus, the interference can be defined as the set of links that can interfere with any given link in the graph G [SGDC08].

6.2.2.1 Contention graph

To define the interference in the graph G, we extract the contention graph $G' = (S', E')$, $S' \subset S$, $E' \subset E \times E$ with $(i', j') \in E'$. To illustrate the contention graph G', we consider a simple network topology consisting of four sensor nodes $S_i, ..., S_n$ for $(i = 1, .., 4)$ as shown in Figure 6.1. Each sensor node is equipped with several radio interfaces represented by small circles, while the links are represented by dotted lines. Each link is labelled with its channel number. Figure 6.1 depicts a network topology with all sensors using channel 1 at the same time. Data transmission cannot be achieved between pairs of nodes when multiple nodes

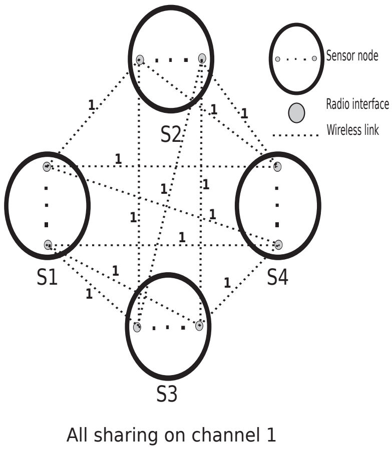

Figure 6.1: All radios sharing the channel 1

transmit because all are tuned to the same channel. Consequently, interference between links and collisions of data packets transmitted over the channel occur leading to a decrease in network performance. The number of channels $C = \{1, 2....k\}$ that can be assigned to each sensor is limited by the number of radio interfaces on each sensor $r_i \leq C$. To indicate whether interference exists on link (i, j), we define $I_{i,j}$ as the interference indicator.

$$I_{i,j} = \begin{cases} 1 & if X(i,j) = X(i',j'), \text{interference exits on link (i, j)} \\ 0 & \text{otherwise, no interference exists on link (i, j)} \end{cases} \tag{6.1}$$

The problem addressed here is to know which channel to use in presence of multiple channels for a given transmission?

6.2.3 Proposition

To alleviate the problem of interference described above, we propose a distributed hybrid channel assignment mechanism called WCDS-CA, as shown in Figure 6.2, in which we assign a unique channel in the network to each radio interface in such a way that the number of distinct channels assigned to adjacent links of any given sensor is at most the number of radio interfaces of that sensor.

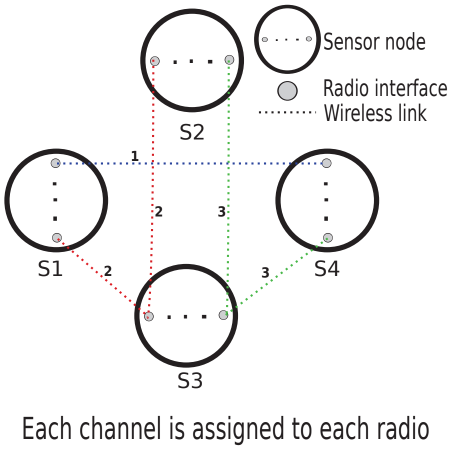

Figure 6.2: Distributed channel assignment

Let M be the number of pairs of links that are assigned a common channel and are connected by a link in G'. Let Z be the total interference on these M links. Our objective is to minimize Z. Hence, we have:

$$Z = min \sum_{(i,j) \in E} I_{i,j} \tag{6.2}$$

In the following Section, 6.10, we present our hybrid assignment method.

6.3 Distributed hybrid channel assignment

In this section, we present our distributed hybrid channel assignment mechanism to reduce interference.

This section is related to *[FMLE10b; FMLE11a; FLE12c; FLZE13]*.

6.3.1 Overview of WCDS-CA

Our WCDS-CA method is an application of graph colouring, in which channels are assigned frequencies corresponding to the colours assigned to sensors.

- Step 1: Classify the nodes in the table in decreasing order according the degree of connectivity. Assign each sensor node its order number in the list.

- Step 2: Going through the list in order, assign a colour not yet used to the first node not yet coloured, and assign the same.
- Step 3: If there are some sensor nodes not coloured in G, go back to step 2; otherwise the assignment of colours is complete (see Algorithm 5).

The construction of WCDS-CA consists of two phases: Tree construction and data forwarding.

- Phase 1: Tree construction

The construction of WCDS-CA is based on the CDS technique. The broadcast tree is constructed incrementally from the sink via a beacon message, by electing parents and leaves based on the degree of connectivity (as shown in Figure 6.3). A CDS of G is a set of parents S' ($S' \subseteq S$), such that every sensor in $S - S'$ is in the neighbourhood of at least one node in S', and the set of parent S' is connected [GP09]. WCDS-CA computes the minimum number of parents in S'.

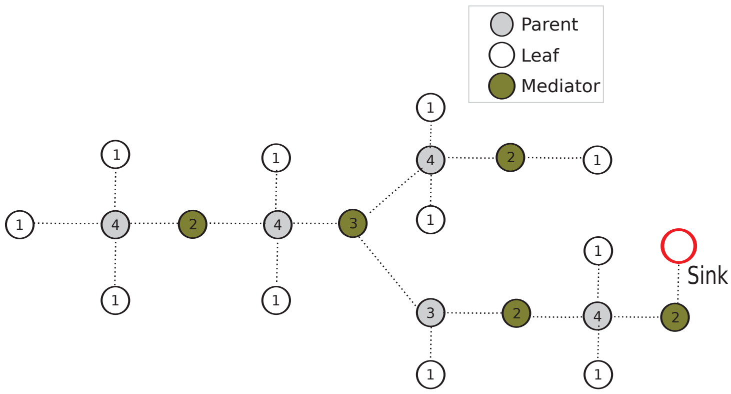

Figure 6.3: WCDS-CA: Broadcast tree

From the resulting tree as shown in Figure 6.3, mediators linking two parents consecutive are elected. From Figure 6.3, we note that, the total number of parents necessary to cover the network, the cardinality of

$$| WCDS - CA | = 5 \leq | CDS | = 10 \tag{6.3}$$

- Phase 2: Data forwarding

To efficiently forward the aggregated data, a set of parents and leaves are assigned to a single fixed channel. Mediators are assigned to several orthogonal channels so that they can dynamically switch to the static channels of parents for aggregating the data. The shortest path between parents and mediators is performed using Dijkstra's algorithm. This allows the data to be efficiently propagated in parallel on different channels from the parent to the mediator to the parent towards the sink in order to reduce the number of individual transmissions as described in Chapter 3, Section 3.2.

Input: Connected graph $G = (S, E)$; Set of channels C.
Output: Distributed Channel Assignment f: $S \longrightarrow C$.

```
for i = 1 to n do
    assign to i color 1
    for i = 1 to n do
        for j = 1 to n do
            if i is adjacent to j and has the same colour,
            (search for a new colour for j) then
                k ⟵ (color of j) + 1;
                for l = 1 to n do
                    if colour of l is k and l is adjacent to j then
                        k ⟵ k + 1;
                        next l;
                        assign colour k to j
                    end
                end
            end
        end
    end
end
```

Algorithm 5: Pseudo-code for a feasible colouring of G

In the following Section, 6.4, we define the performance metrics.

6.4 Performance metrics

The following performance metrics are used to evaluate our proposed approach in a 802.11b-based WSN.

- Interference

Interference is the number of pairs of links that are assigned to a common channel and are connected by a link in G'.

$$Interference = max \sum_{(i,j)\in E} I_{i,j} \tag{6.4}$$

- Sink throughput

Sink throughput is the total number of data packets received by the sink in a period of time. The higher the value of the sink throughput the better is the network performance.

$$\text{Sink throughput} = \frac{\sum_{i=1}^{n} P_{Received_i} * P_{Size}}{SIMU_{Time}} \tag{6.5}$$

$P_{Received}$ is the total number of data packets received by the sink, P_{Size} is the size of a packet, $SIMU_{Time}$ is the simulation time and n is the number of sensors.

- Broadcast latency

Broadcast latency is the time taken between the first data packet transmission by parents along the tree and the last data packet received by the sink. Broadcast latency indicates the promptness of data delivered to the sink with lower latencies being more desirable.

$$\text{Broadcast latency} = T_{Received} - T_{Ransmission} \tag{6.6}$$

$T_{Received}$ is the reception time by the sink, $T_{Transmission}$ is the transmission time by each parent.

- Energy Consumed

The energy model used is the same as in Chapter 4, Section 4.5.

- Routing Overhead

As we mentioned earlier, the tree is built out from the sink via a beacon message. Each sensor in the network receiving the beacon message, adds its degree of connectivity in the beacon and forwards it to the next sensor and so on. At the end, each sensor elects its parent based on the degree of connectivity. In the case of a failure of a parent, each leaf performs the same operation in order to identify its parent responsible for transmitting the data. Each beacon exchanged in a data packet. We want to evaluate the ratio of the total number of beacon messages exchanged (to discover, update and maintain the paths) by the sensors to the total number of packets that are received by the sink. Routing overhead is the percentage of the total number of packets exchanged to the total number of packets that are received by the sink and the lower the routing overhead the better it is.

$$\text{Routing Overhead} = \frac{\sum_{i=1}^{n} P_{Exchanged_i} * 100}{P_{Received}} \tag{6.7}$$

$P_{Exchanged}$ is the total number of packets exchanged by the sensors.

In the following Section, 6.5, we describe the simulation set-up and present the comparative results.

6.5 Simulation set-up and Comparative results

6.5.1 Simulation set-up

We implemented a simulation of our WCDS-CA using MatLab [Mol70], we used network sizes that vary from 50 to 400 sensors generated in a square area 1000m x 1000m. In all the analysis, the number of channels C was varied from 1 to 4 while the number of radio interfaces for each sensor node was a random quantity varying between 2 to 10. To validate our analysis, we repeated the experiments 20 times using the same network topology. The averaged value of these 20 runs are presented. We consider a network topology consisting of 184 sensor nodes

Table 6.1: Simulation Parameters Used

Parameters	**Description**	**Value**
E	Initial energy for each sensor	10^4 (J)
E_{elec}	Energy to run transc/receiver	50 (nJ/bit)
L	Simulation area (m)	1000 X 1000
Traffic rate	UDP traffic	3 packets/sec
MAC	MAC layer	IEEE 802.11b
C	Number of channels	$1-4$
Radio	Radio propagation	Log-Shadowing
Routing	Routing protocol	Dijkstra
S	Sensor placement	Random
E_{amp}	Energy of amplifier	100 (pJ/bit)
P_{Size}	Packet size	32 bytes
$SIMU_{Time}$	Simulation time	1000 s
B	Bandwidth	250 (kbps)
R	Locality radius (m)	30m
N	Number of sensors	184
Sink	Number of sinks	1

with 498 wireless links, where 42 parents are elected based on the degree of connectivity. The sink is chosen randomly among the parent nodes and it is fixed as shown in Figure 6.4. Mediators lie between two parents as shown in Figure 6.4. Each sensor in the network generates a packet every 3s. To evaluate the performance and efficiency of our proposed WCDS-CA method, we compare the performance of WCDS-CA with two other previously proposed approaches: one using a single channel and another approach Sensor Multi-Channel Medium Access Control (SMC MAC) presented by [RR09] using the cited performance metrics. Interference, sink throughput, broadcast latency, routing overhead and energy consumed.

In SMC MAC, all the sensors are equipped with a single half-duplex transceiver and use a dedicated control channel and eight data channels to dynamically switch from one channel to another. The channel negotiation is done using request to send and clear to send frames. For a transmission between three consecutive sensors, the request to send timeout value of the intermediate sensor is increased in order to alleviate the hidden terminal problem. From a simulation point of view, the performance of SMC MAC gives better results than the single channel in terms of throughput and latency. However, the authors do not propose how to assign a specific channel to each radio in the presence of multiple distinct channels. A single channel is dedicated for the control data thereby reducing the capability of using distinct channels. In addition, the authors do not address the switching delays incurred when switching from one channel to another during the transmission which is important when evaluating the data delivery latency. As in WSNs, the data transmission is made from many (all the sensors) towards a single sink. SMC MAC just performs better for one to one transmission instead of many to one transmission as in our approach. In contrast with our proposed WCDS-CA method, we determine the number of channels that are needed over all sensors in such a way that adjacent nodes are assigned to distinct channels.

6.5.2 Comparative results

Figure 6.4 shows the feasible assignment of the graph. We see leaves and parents operating on the single fixed channel, while mediators linking two consecutive parents operating with several orthogonal channels.

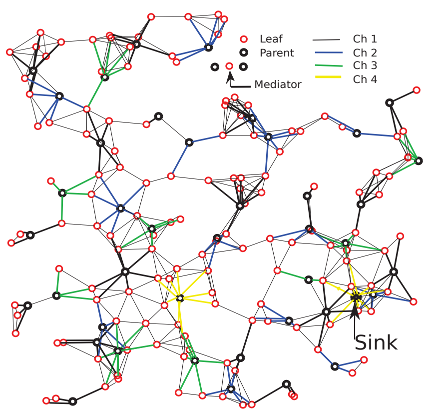

Figure 6.4: Feasible colouring graph

- Impact of number of common links on each channel.

Figure 6.5 shows the case of a single channel where all communications are made simultaneously on a single channel. It shows the number of common links against the number of sensors when using each sensor node both for communications and routing. We observe from Figure 6.5 that sensor nodes 30, 42, 43, 75 and 183 have a greater number of common links because they have many neighbours. This means that the probability that interference occurs at these nodes is higher. More precisely, the maximum number of common links used per sensor node to communicate with and send the data to its neighbours in this case is around 37. The mean number of common links is around 14, and the minimum is around 2. We recall that, in this case, there is no channel assigned to a particular sensor node. Every node can communicate with any other if they are within its communication range.

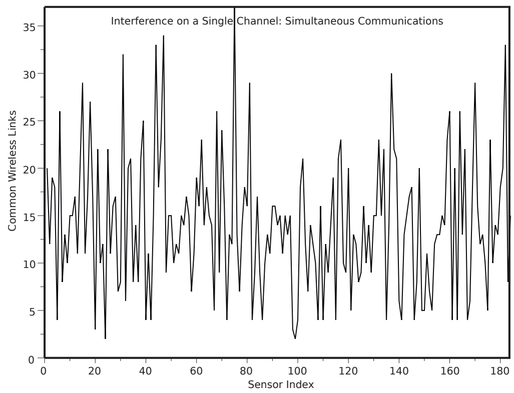

Figure 6.5: Interference on a single channel

Next, we evaluate the number of common links used by each sensor node when several channels are used. When we consider channel 1, as shown in Figure 6.6, we observe that the maximum number of common links per node using this channel is around 14. The mean number of common links is around 5. In the case of channel 2, as shown in Figure 6.7, we note that the maximum number of common links used by each sensor node is around 12, and the mean value is around 3. Figures 6.8 and 6.9 depict a roughly similar number of common links, but with mean values of 3 and 2 for channel 3 and 4 respectively.

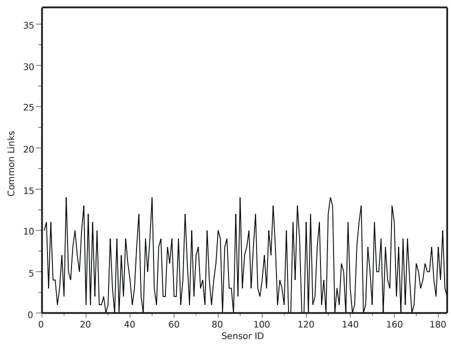

Figure 6.6: Interference on channel 1: Simultaneous communications

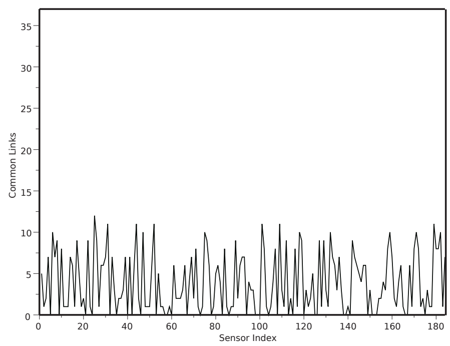

Figure 6.7: Interference on channel 2: Simultaneous communications

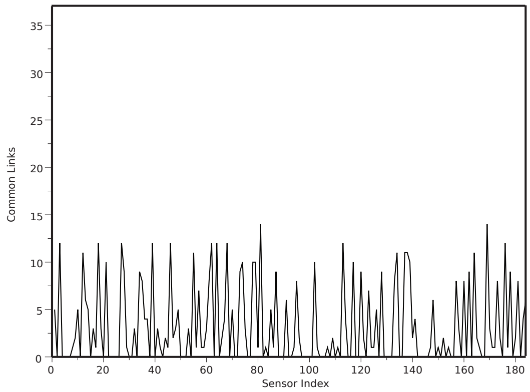

Figure 6.8: Interference on channel 3: Simultaneous communications

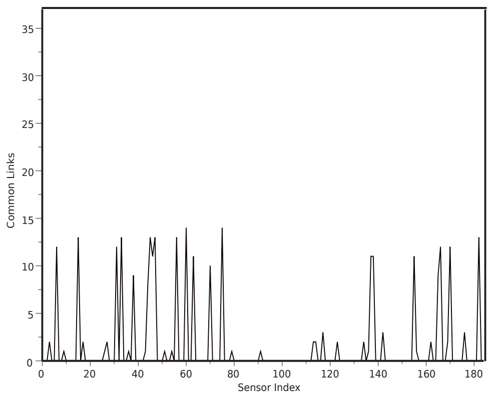

Figure 6.9: Interference on channel 4: Simultaneous communications

It is worthwhile noting, from the above results, that the maximum number of common links decreases to around 62% for channels 1, 3 and 4, and 67% for channel 2 compared to the values obtained when a single channel is used. Considering the mean value of the number of common links, we also observe better results for the mean value of common links as shown by the decrease of around 64% for channel 1, 71% for channel 2, 78% for channel 3 and 85% for channel 4.

From the topology shown in Figure 6.4, the broadcast tree based on Breadth-First Search (BFS) is built out from the sink taking into account the sensor degree of connectivity. Thus, data transmission takes place in breadthwise along multiple hops over each channel from parent to mediator to parent towards the sink. The resulting broadcast tree is showed in Figure 6.10. The broadcast tree consists of 42 parents, and mediators lie between two parent nodes. In this broadcast tree, we want to evaluate the number of data transmitted from parent to mediator to parent towards the sink.

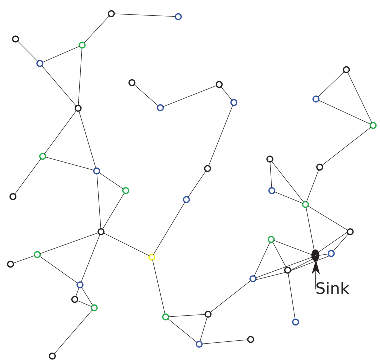

Figure 6.10: WCDS-CA: Broadcast Tree based on BFS

- Evaluation of sink throughput on each channel.

Figure 6.11 shows the throughput received by the sink for each channel used. We note that in all the three cases, when the number of channels and radio interfaces used per sensor node increases, the sink throughput increases. In the case of a single channel where all transmissions are made simultaneously on channel

1, the maximum sink throughput is 700 bps. An improvement is seen with SMC MAC using 4 channels with the maximum sink throughput increasing to around 1300 bps. WCDS-CA outperforms both, with the maximum sink throughput reaching 1450 bps, again using 4 channels.

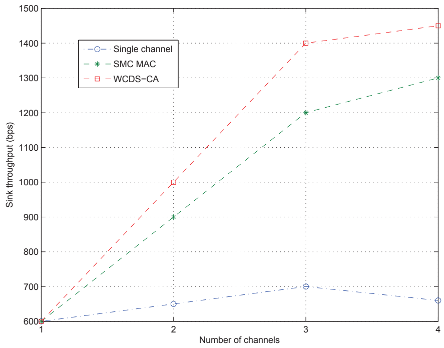

Figure 6.11: Evolution of sink throughput on each channel

Table 6.2: Throughput with Single, SMC MAC, and WCDS-CA

Methods	Single	SMC MAC	WCDS-CA	Improv with SMC MAC over Single	Improv with WCDS-CA over Single	Improv with WCDS-CA over SMC MAC
Throughput	46%	86%	96%	46.15%	51.72%	10.35%

Table 6.2 shows the percentages of useful sink throughput on each channel and the percentages improvement with SMC MAC over single, WCDS-CA with single and WCDS-CA with SMC MAC respectively. We can see that WCDS-CA outperforms SMC MAC and the single channel for the maximum sink throughput due to the hybrid assignment of channels.

- Impact of network density on sink throughput.

Figure 6.12 shows that, when we vary the number of sensors from 50 to 400, the maximum sink throughput increases for all three techniques. When the number of sensors is less than 70, the single channel performs better than WCDS-CA with an average maximum sink throughput around 500 bps. This is because in WCDS-CA, under lower network density, some sensors will not be connected together creating a disconnected network in which parents and leaves are not connected. We can also observe that, when the number of sensors is less than 80, SMC MAC performs better than both WCDS-CA and the single channel. This is because in SMC MAC, the dedicated control channel for the channel negotiation performs better for lower network density. An interesting result is that, when the number of sensors is 200, WCDS-CA and SMC MAC achieve the same maximum sink throughput of around 1000 bps. In dense networks (i.e., more than 200 sensors), WCDS-CA outperforms SMC MAC and the single channel with maximum sink throughputs reaching around 1430, 1350 and 800 bps respectively. This is because SMC MAC and the single scale well for one to one transmission rather than many to one.

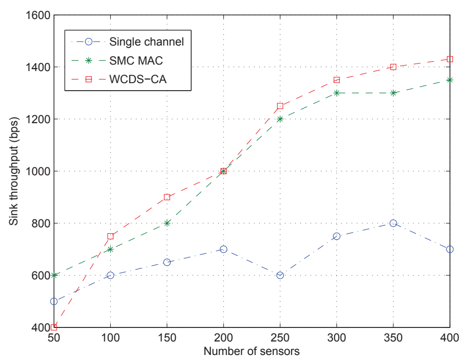

Figure 6.12: Evolution of sink throughput with network density

Table 6.3 shows percentages of useful sink throughput and the percentages improvement with SMC MAC over single, WCDS-CA with single and WCDS-CA with SMC MAC respectively with different network densities. The results show that WCDS-CA scales better with the density of the network than with SMC MAC and the single channel.

Table 6.3: Throughput with Single, SMC MAC, and WCDS-CA

Methods	Single	SMC MAC	WCDS-CA	Improv with SMC MAC over Single	Improv with WCDS-CA over Single	Improv with WCDS-CA over SMC MAC
Throughput	53%	90%	95%	41.11%	44.22%	5.26%

- Impact of broadcast latency on each channel.

Broadcast latency indicates the promptness of data delivered to the sink and therefore needs to be minimized. As mentioned previously, leaves can only sense and transmit their measurements to their parents. Parents aggregate the data from leaves before forwarding it towards the sink via mediators. Figure 6.13 shows

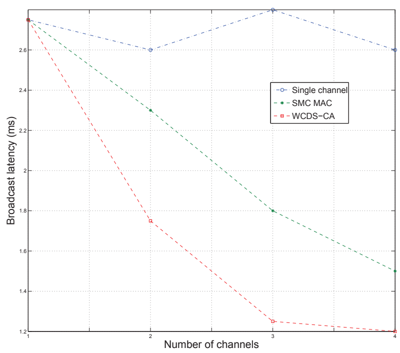

Figure 6.13: Broadcast latency on each channel $1, 2, 3, 4$

that the broadcast latency decreases when the number of channels increases in WCDS-CA and SMC MAC, but not for the single channel. In the case where all the sensors send the data packets using channel 1, all the three methods have the same average broadcast latency of around 2.75 ms. Broadcast latency in the case of a single channel decreases between approximately [2.75 - 2.6] ms. When the number of channels increases from 2 to 4, the broadcast latency decreases between

[2.75 - 1.5] ms and [2.75 - 1.2] ms in SMC MAC and WCDS-CA respectively. In terms of broadcast latency, WCDS-CA outperforms the other schemes.

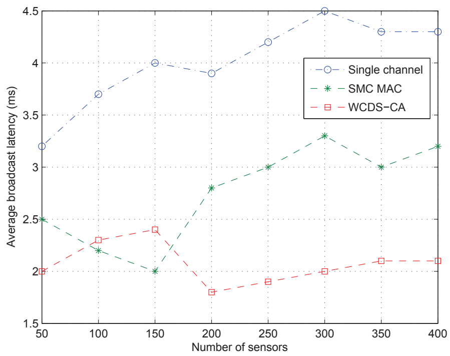

Figure 6.14: Variation of average broadcast latency with sensor density

- Impact of network density on broadcast latency.

Figure 6.14 shows that, when the number of sensors varies from 50 to 400, the single channel yields the worst results, with broadcast latency varying between 3.2 and 4.5 ms. An improvement is obtained with SMC MAC, where the broadcast latency varies between 2 and 3.3 ms. That is due to the fact that in SMC MAC, all the sensors are equipped with a single half-duplex transceiver and use a dedicated control channel and eight data channels to dynamically switch from one channel to another in order to alleviate the hidden terminal problem. The lowest broadcast latency is obtained with WCDS-CA, varying between 1.8 and 2.4 ms. From Figure 6.14, we observe that when the number of sensors varies between 100 and 150, SMC MAC achieves lower latency than WCDS-CA and the single channel. Statistically, we note that using WCDS-CA can reduce the minimum broadcast latency by around 10% and 47% relative to SMC MAC and the single channel respectively.

- Energy consumption on each channel.

Figure 6.15 shows the results of the average energy consumed on each channel to deliver the data to the sink. In our analysis, we considered the energy used to transmit and receive the data as described previously. We note that when only a single channel is used to deliver the data packets towards the sink, the energy used in delivering the data for all the three methods is around 45 mJ. As the number of channels increases, the energy used decreases considerably for both WCDS-CA and SMC MAC. This is because the data are transmitted in parallel along multiple channels instead of a single channel.

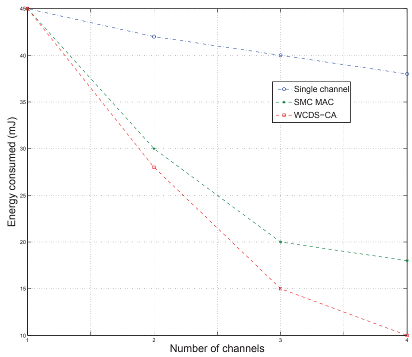

Figure 6.15: Evolution of energy consumed on each channel $1, 2, 3, 4$

Table 6.4 presents the maximum and minimum energy consumption used with each method. WCDS-CA consumes the least energy compared to the two other approaches. WCDS-CA can reduce the maximum energy consumed by about 77%, SMC MAC by about 60% and the single channel by about 15%. Statistically, we can see that WCDS-CA reduces the energy consumed by about 6.66%, 25% and 44.4% over SMC MAC on channels 2, 3 and 4 respectively.

- Impact of network density on energy consumption.

Figure 6.16 depicts the average energy consumed as a function of network density. We observe that, as the network density varies between $[50 - 400]$ sensors, the energy consumed in the single channel varies between $[38 - 67]$ mJ. An improvement is obtained with SMC MAC, where it varies between $[30 - 64]$ mJ. The lowest energy consumed is obtained with WCDS-CA with the average energy consumed varying between $[23 - 57]$ mJ.

Table 6.5 shows the maximum and minimum energy used by various approaches with different network densities. As the network density varies between

Table 6.4: Energy consumed with Single, SMC MAC, and WCDS-CA

Methods	Single	SMC MAC	WCDS-CA	Improv with SMC MAC over Single	Improv with WCDS-CA over Single	Improv with WCDS-CA over SMC MAC
Maximum energy consumption (mJ)	45 mJ	45 mJ	45 mJ	0 mJ	0 mJ	0 mJ
Minimum energy consumption (mJ)	38 mJ	18 mJ	10 mJ	20 mJ	28 mJ	8 mJ
Decrease in energy consumption (%)	15%	60%	77%	52.63%	73.68%	44.44%

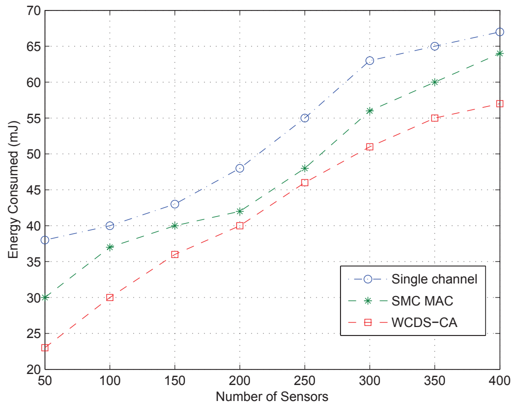

Figure 6.16: Variation of energy consumed with network density

Table 6.5: Maximum and Minimum Energy consumed by Single, SMC MAC, WCDS-CA

Methods	Single	SMC MAC	WCDS-CA	Improv with SMC MAC over Single	Improv with WCDS-CA over Single	Improv with WCDS-CA over SMC MAC
Maximum energy consumption (mJ)	67 mJ	64 mJ	57 mJ	3 mJ	10 mJ	7 mJ
Minimum energy consumption (mJ)	38 mJ	30 mJ	23 mJ	8 mJ	15 mJ	7 mJ
Decrease in energy consumption (%)	43.28%	53.12%	59.64%	21.05%	39.47%	23.33%

[50 − 400] sensors, the energy used to transmit the data increases for all methods. WCDS-CA outperforms both the single channel and SMC MAC approaches. This is because the single and SMC MAC approaches use the simple flooding technique in their route discovery process. Each beacon exchanged in a data packet during the route discovery process to find the routing paths consumes a certain amount of energy. With our approach, once the tree is built, each sensor elects locally its parent for transmitting the data. Our proposed approach does not to rebuild the tree several times and consequently needs less beacon messages to find and forward the data towards the sink which ultimately result in energy saving compared to the SMC MAC and the single channel techniques.

- Impact of routing overhead on each channel.

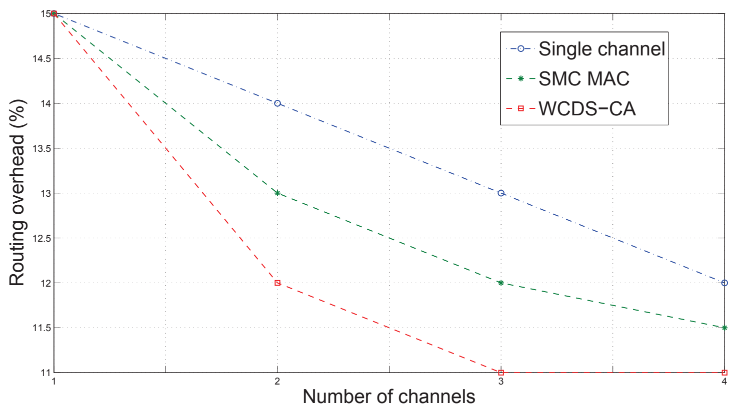

Figure 6.17: Evolution of routing overhead on each channel

Figure 6.17 shows that, our approach uses a lower number of beacon messages compared to SMC MAC and the single channel to find, establish and maintain the route in the network. This is because once the tree is built, each sensor knows the degree of connectivity of its single hop neighbourhood and saves this information in its memory. When failures occur, the election of the parent is made locally, and there is no need to have a global knowledge of the network. Our proposed approach improves routing overhead by about 5% and 10% over the SMC MAC and the single channel approaches respectively.

In the following Section, 6.6, we summarize the chapter.

6.6 Summary

In this chapter, we have presented a distributed hybrid algorithm to perform a selection of communication channels in a WSN. A tree is built out from the sink, electing sensors with the highest degree of connectivity as parents, and sensors with the lowest degree of connectivity as leaves. Parents and leaves are assigned to a single static channel. Mediators, are assigned to several orthogonal channels so that they can dynamically switch to the static channels of the parents to collect data. This allows the data to be efficiently propagated in parallel on multiple channels from the parent to the mediator to the parent towards the sink. We have showed that our approach outperforms SMC MAC and the single channel in terms of interference, sink throughput, broadcast latency, routing overhead and energy consumption. Table 6.6 summarizes the advantages and disadvantages of previous approaches discussed.

In the short term, we will take into account the tree maintenance in the case where a parent or a mediator fails. We will study how the tree will be reconstructed in such a way that it does not affect the overall network topology. Finaly, we will apply MERCP present on mediators, in order to improve data aggregation process.

In the following Chapter 7, we summarize the contributions presented in this thesis and present the perspectives.

Approach	Strategy	Advantages	Disadvantages
[MDS10]	Static	Low interference, High throughput	High overhead, No energy saving
[WSHL08]	Static	Low interference and latency, High throughput	Not efficient in dynamic conditions, need global knowledge
[WM10]	Static	Low interference, Efficient routing, Works with existing hardwares	No energy saving, High overhead
[JDM11]	Static	Low interference, Efficient routing	High complexity and overhead, Not distributed
[RR09]	Static	Efficient routing	No energy saving, Need global knowledge, Not works with existing hardwares
[JX11]	Dynamic	Low interference, Efficient routing, High throughput	High overhead and delay
[RBAB06]	Dynamic	Low interference, Efficient routing, Works with existing hardwares	No energy saving, High overhead
[GGCS10]	Dynamic	High throughput, Energy saving, Works with existing hardware	Need global knowledge, High overhead
[RRT+11]	Hybrid	High throughput, Lower delay	No energy saving, Need global knowledge
[KV06]	Hybrid	Alleviate hidden problem	Not good in many to one transmission, High overhead, Lower possibility to assign distinct channels
WCDS-CA (Proposed approach)	**Hybrid**	**Efficient routing, Energy saving, Low interference, No need global knowledge**	**Not suitable with existing hardware due to switching among radios**

Table 6.6: Summary of previous approaches

Chapter 7

Conclusions and Perspectives

Wireless Sensor Networks (WSNs) have been designed for gathering the data and send back to users via the sink. In WSNs, each sensor node is equipped with a small battery and communicate with its neighbours over wireless connections. When sensors transmit the data, they use their energy in transmission. Thus, the sensor energy is the main impediment for improving overall WSN performance such as lifetime. A critical aspect in the design of WSNs is to save energy and keep the network functional for as long as possible. Our objective in this thesis was to propose to reduce the number of transmissions in order to enhance the network lifetime. We address this issue by investigating simultaneously aggregation, routing and channel assignment sub-issues. We propose a global solution that aims to enhance the network lifetime. The key concepts introduced are: degree of connectivity in tree-based aggregation, multipath routing between sensors and mini-sinks, parents, leaves, mediators and channel assignment in aggregating nodes. Finally, we present the perspectives of our work.

7.1 Conclusions

7.1.1 Tree-based Data Aggregation Schemes in WSNs

In Chapter 3, we have suggested three tree-based data aggregation algorithms: Depth-First Search Aggregation (DFSA), Flooding Aggregation (FA) and Well

Connected Dominating Set Aggregation (WCDSA), that aim to reduce the number of transmissions from each sensor towards the sink. Building the tree is helpful because the maximum amount of data receives by the sink provides the most useful information and does not need to have global knowledge of the entire network. The degree of connectivity of a sensor is then taken into account in the tree construction, by electing sensors having the highest degree of connectivity as parents, and sensors having the lowest degree of connectivity as leaves. As a result, only the set of parents needs to transmit data towards the sink. The shortest path between parents and the sink is extracted using Dijkstra's algorithm for forwarding purposes. Thus, data transmission takes place along the shortest path from parent to parent towards the sink in order to reduce the number of individual transmissions by each sensor. As the sink is the final recipient of the gathered data, its locations is very crucial to receive all the data. In addition, we have studied the effect of sink location on aggregation efficiency through many topologies.

Extensive simulations have been performed and the results have been compared with some existing algorithms such as Breadth-First Search (BFS), Depth-First Search (DFS) and flooding. Simulation results have showed that the results of the minimum number of data packets transmitted towards the sink and the maximum number of leaves in each algorithm varies for each position of the sink chosen. For all the positions of the sink chosen, WCDSA outperforms better than BFS, FA, DFSA and DFS respectively due to the using of mediators during the data transmission.

7.1.2 Efficient Tree-based Aggregation and Processing Time in WSNs

In Chapter 3, we have seen that tree-based data aggregation is an efficient technique to reduce the number on transmissions by each sensor in the network, by electing parents and leaves. These data aggregated by parents may suffers from increased data delivery time because the parents must wait for the data from their leaves. As the network topology can be random, some parents might have many leaves, making it very expensive for a parent to store all incoming data in its buffer. If a parent waits for the data from its leaves for long time, it collects more data and hence data aggregation gain may increase. Thus, we need to determine the time taken by parents to aggregate and process the data, because it takes more time to aggregate and process the data than to transmit the data towards the sink. In Chapter 4, we have suggested an Efficient Tree-based Aggregation and Processing Time (ETAPT) algorithm using the Appropriate Data Aggregation and Processing Time (ADAPT) metric to ensure that the data aggregation and processing time in parents is appropriate. Given the maximum acceptable latency, ETAPT's calculation takes into account the position of parents, their number of leaves and the depth of the tree, in order to compute an optimal ADAPT time for parents with more leaves in order to increase the data aggregation gain, thus ensuring enough time to process the data from leaves.

Performance evaluation has been carried out in order to validate ETAPT and the results have been compared with those proposed by [ZWR+10] and [CLL+06]. The results obtained show that our ETAPT provides a higher data aggregation gain with lower energy consumption and aggregation time compared to existing approaches. Our suggested ETAPT algorithm is particularly useful in resource-constrained networks since it does not need synchronization among sensors in the network.

7.1.3 Mobility of Mini-Sinks for Reducing Congestion in WSNs

We have seen in Chapter 3 and 4 that, tree-based data aggregation could be an efficient technique for reducing the energy consumption of sensors, by reducing the individual data transmitted by each sensor. As sensors are equipped with a limited amount of storage capacity. Some parents may fail to transmit or receive the data from other parents or leaves because the amount of data collected becomes greater than the amount of data that can be forwarded. Thus, causing the emergence of local congestion at these parents and increasing the amount of data loss. To alleviate that, we have proposed in Chapter 5 the introduction of mobile elements in the network to enhance this limitation. So, instead of having a central sink responsible for all data aggregation, introducing multiple data aggregators, called Mini-Sinks (MSs). MSs move in the sensor field according to a random mobility model in order to maintain a fully-connected network topology, aggregating the data within their coverage areas based on the controlled Multi-path Energy Conserving Routing Protocol (MECRP) and forwarding it towards the sink. MECRP, is implemented in MSs and sensors in order to optimize the transmission cost of the forwarding scheme. Thus, a set of multiple paths between MSs and sensors is generated to distribute the global traffic, so as to reduce the appearance of congestion over the entire network.

Simulations have been made and the results have been compared with those for a single and mobile sink proposed by [IKN06]. The obtained results have showed that our proposition achieves 95% of packet delivery ratio, 94% of throughput, 69% of end-to-end delay, 93% of network lifetime, 7.75% of energy overhead and 13% of multiple paths overhead. The results showed that for a network consisting of 100 sensors, the using of 30 MSs is enough to maintain a fully-connected network topology. Thus, the mobility of MSs help to relax the requirement on network connectivity and reduce congestion appearance since the transmission of data from sensors is done through a single hop to MSs.

7.1.4 Multi-Channel Assignment in Multi-Radio WSNs

In Chapter 3 and 4, we have seen that leaves can only transmit to parents. During the transmission of data, two parents may interfere with transmissions along other communication links if they transmit on the same channel at the same time. Sensors may use be equipped with several radio interfaces which they may use to communicate with several neighbours. Inefficient data transmission cannot be achieved between pairs of parents when more than one parent is transmitting. Consequently, interference between links and collisions of data packets. We have been interested by knowing which channel to use in presence of multiple channels for a given transmission. We have proposed in Chapter 6, a distributed hybrid channel assignment called Well Connected Dominating Set Aggregation (WCDS-CA), in which we assign a unique channel in the network to each radio interface in such a way that the number of distinct channels assigned to adjacent links of any given sensor is at most the number of radio interfaces of that sensor. After have been build the tree, electing sensors with the highest degree of connectivity as parents, sensors with the lowest degree of connectivity as leaves and mediators linking between two parents are elected. Parents and leaves are assigned to a single static channel. Mediators, are assigned to several orthogonal channels so that they can dynamically switch to the static channels of parents for aggregating the data. This allows the data to be efficiently propagated in parallel on multiple channels from the parent to the mediator to the parent towards the sink.

We compare the results obtained with our proposed approach with those obtained for single and Sensor Multi-Channel Medium Access Control (SMC MAC) presented by [RR09] using performance metrics such as interference, sink throughput, broadcast latency, energy consumption and routing overhead. We demonstrate that our approach achieves better performance results over previous approaches.

7.2 Perspectives

Related to aggregation issue, in the short term:

- We will take into account the tree maintenance.

Whenever a packet is lost at a given level of the tree due to link or sensor failures, data coming from the subordinated levels of the tree is lost.

- Study the relationship between waiting time and data aggregation gain in order to make it scalable in more complex WSNs.

- Apply our MERCP on mediators, in order to improve data aggregation process.

- Evaluate the impact on energy consumption during data aggregation by parents.

- Vary the length of the data packet in order to evaluate the impact on energy consumption.

- Evaluate the cost in terms of time and energy to construct the tree.

Related to routing, we will:

- Evaluate the impact of interference between sensors and MSs during the forwarding procedures.

- Evaluate the high cost of maintaining the tree in dynamic networks.

As the data gathered by sensors could be similar, in the long term:

- Consider the correlation of data transmitted in order to mitigate the problem of reporting similar data by close sensors.

- Integrate into a simulator all the algorithms proposed.

- Analyze the overall overhead with the scalability.

- Set-up a testbed applied for example to a real application such as environmental monitoring.

Author's Publications

- ☐ D. Fotue and T. Engel. An ad-hoc Wireless Sensor Networks with Application to Air Pollution Detection. In the First International Conference on Sensor Networks and Applications (SNA), pp. 48-53, November 4-6, San Francisco, California, USA, 2009 [FE09].

- ☐ D. Fotue, F. Melakessou, H. Labiod and T. Engel. Design of an Enhanced Energy Conserving Routing Protocol (ECRP) based on Route Diversity in Wireless Sensor Networks. In the 9^{th} IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), pp. 1-7, 23-25 June, Juan Les Pins, France, 2010 [FMLE10a].

- ☐ D. Fotue, F. Melakessou, H. Labiod and T. Engel. Design of New Aggregation Techniques for Wireless Sensor Networks. In the 18^{th} Annual IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS), pp. 400-402, 17-19, August, Miami, Florida, USA, 2010 [FMLE10b].

- ☐ D. Fotue, F. Melakessou, H. Labiod and T. Engel. Effect of Sink Location on Aggregation Based on Degree of Connectivity for Wireless Sensor Networks. In the Fifth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), pp. 271-276, June 30 - July, Seoul, Korea, 2011 [FMLE11b].

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☐ D. Fotue and H. Labiod. "Efficient Tree-based Aggregation and Processing Time for Wireless Sensor Networks." Submitted to IEEE Gobal Communication Conference (Globecom), 2014 [FLE14].

☐ D. Fotue, S. Zeadally and H. Labiod. "Improving Performance with Multi-Channel Assignment in Multi-Radio Wireless Sensor Networks." Submitted in the Ad Hoc Network Journal (Elsevier), 2013 [FLZE13].

Appendix 1

The resulting trees constructed of BFS, DFS, $DFSA$, FA and $WCDSA$ described in Chapter 3, with each sink location can be seen below.

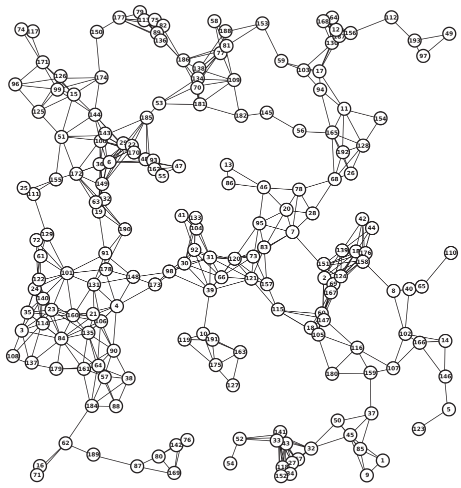

Figure 1: Initial topology consisting of 193 sensors

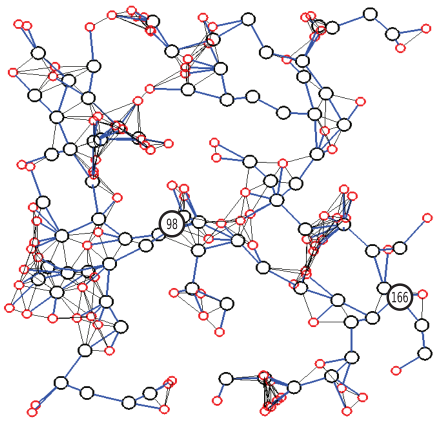

Figure 2: BFS: Resulting Tree with different locations of the sink

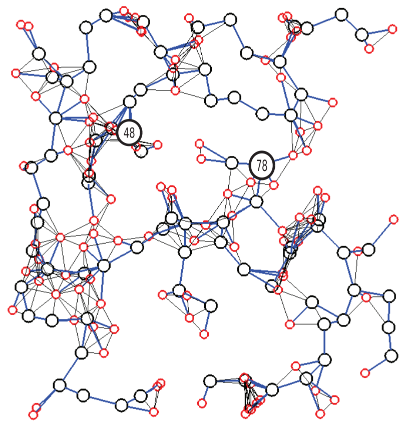

Figure 3: DFS: Resulting Tree with different locations of the sink

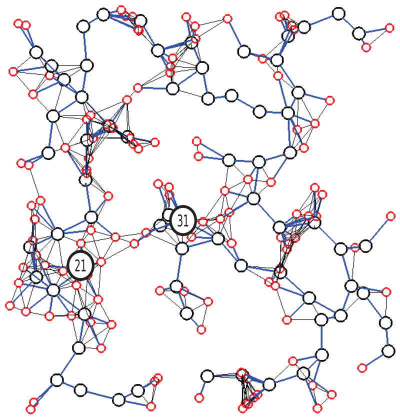

Figure 4: DFSA: Resulting Tree with different locations of the sink

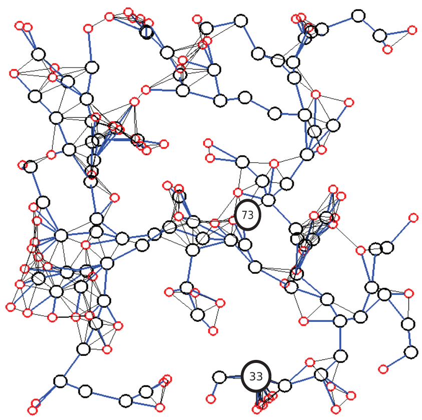

Figure 5: FA: Resulting Tree with different locations of the sink

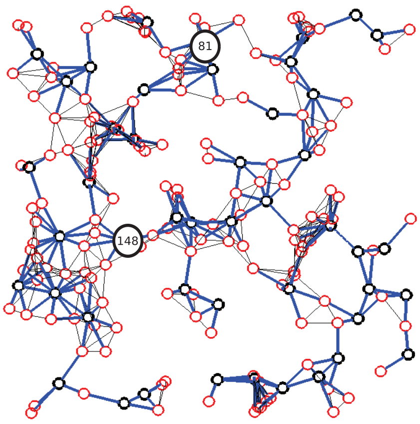

Figure 6: WCDSA: Resulting Tree with different locations of the sink

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RESUME

Les Réseaux de Capteurs Sans Fils (RCSFs) ont pris beaucoup d'importance dans plusieurs domaines tels que l'industrie, l'armée, la pollution atmosphérique etc. Les capteurs sont alimentés par des batteries qui ne sont pas faciles à remplacer surtout dans les environnements peu accessibles tels que les champs de bataille, les zones volcaniques actives etc. L'énergie de chaque capteur est considérée comme la source première d'augmentation de la durée de vie des RCSFs. En effet, le défaut de fonctionnement d'un capteur dû au manque d'énergie affecte non seulement le capteur lui-même, mais aussi sa capacité à transmettre les données à d'autres capteurs. Puisque la transmission de données est plus coûteuse en consommation d'énergie que la mesure et le traitement, notre préoccupation première est de proposer une technique efficace de transmission des données de tous les capteurs vers le sink tout en réduisant la consommation en énergie. Le sink est le destinataire final de toute les données mesurées. Nous abordons cette question en proposant une solution globale adressant Ã l'agrégation, routage aussi bien que l'allocation des canaux. Nous suggérons trois algorithmes d'agrégation de données basée sur la construction d'arbres: Depth-First Search Aggregation (DFSA), Flooding Aggregation (FA) et Well-Connected Dominating Set Aggregation (WCDSA) qui permettront de réduire le nombre de transmissions de chaque capteur vers le sink. Dans chaque algorithme proposé, le degré de connexité des capteurs est pris en compte dans la construction de l'arbre de telle sorte que les capteurs ayant un degré de connexité élevé sont choisis comme parents, et les capteurs ayant un degré de connexité faible sont choisis comme feuilles. En conséquence, les données pourront efficacement être transmises via le chemin le plus court à travers plusieurs sauts de parent à parent

vers le sink, réduisant ainsi le nombre de transmissions individuelles. Notre approche permet l'optimisation locale pour l'économie d'énergie qui peut être utilisée dans des configurations denses.

L'agrégation des données basée sur la construction d'arbres souffre du délai de délivrance de données parce que les parents doivent attendre de recevoir les données de leurs feuilles. Puisque la topologie du réseau varie aléatoirement, certains parents pourraient avoir beaucoup de feuilles, et il serait alors assez coûteux pour un parent de stocker toutes les données entrantes dans sa mémoire. Ainsi, nous devons déterminer le temps que chaque parent doit mettre pour agréger et traiter les données de ses feuilles, parce qu'il en prend plus pour agréger et traiter les données que pour les transmettre vers le sink. Si un parent attend de recevoir les données de ses feuilles pendant longtemps, il augmente le gain d'agrégation, mais également le temps de délivrance des données au sink. Nous proposons un algorithme, Efficient Tree-based Aggregation and Processing Time (ETAPT) qui utilise la métrique Appropriate Data Aggregation and Processing Time (ADAPT). Etant donné la durée maximale acceptable, l'algorithme ETAPT prend en compte la position des parents, le nombre de feuilles et la profondeur de l'arbre pour calculer l'ADAPT optimal. Les parents ayant plus de feuilles se verront allouer un ADAPT approprié, afin d'augmenter le gain d'agrégation et de disposer de suffisamment de temps pour traiter les données des feuilles. Les résultats obtenus montrent que notre approche permet d'obtenir un grand gain d'agrégation, une faible consommation en énergie et un temps d'agrégation relativement faible.

A n'importe quel moment pendant l'agrégation des données par les parents, il peut arriver que la quantité de données collectées soit très grande et dépasse la quantité de stockage maximale de données que peut contenir leurs mémoires. Pour éviter cela, nous proposons l'introduction dans le réseau de plusieurs collecteurs de données appelés Mini-Sinks (MSs). Ces MSs sont mobiles et se déplacent selon un modèle de mobilité aléatoire dans le réseau pour maintenir la connectivité afin d'assurer la collecte contrôlée des données basée sur le protocole de routage Mulipath Energy Conserving Routing Protocol (MECRP). Un ensemble de chemins multiples est donc généré entre les MSs et les capteurs pour distribuer le trafic global dans le réseau. Les résultats de simulations ont montré que notre approche permet d'obtenir des résultats meilleurs que les approches existantes. Plusieurs simulations ont été faite pour valider notre approche. Nous avons montré que notre solution permet d'obtenir de meilleurs résultats en termes de pourcentage de paquets délivrés, throughput, end-to-end délai, durée de vie du réseau, énergie résiduelle et overhead.

Les capteurs peuvent être équipés de plusieurs interfaces radios partageant un seul canal sans fil avec lequel ils peuvent communiquer avec plusieurs voisins. La transmission des données à travers une liaison de communication entre deux parents peut interférer avec les transmissions d'autres liaisons si elles transmettent à travers le même canal. En conséquence, l'interférence entre les liaisons et la perte des paquets transmis. Nous avons besoin de savoir quel canal utiliser en présence de plusieurs canaux pour une transmission donnée Nous proposons une méthode distribuée appelée: Well Connected Dominating Set Channel Assignment (WCDS-CA), pour calculer le nombre de canaux qui seront alloués à tous les capteurs de telle sorte que les capteurs adjacents se voient attribués des canaux différents. Dans notre méthode, les parents et les feuilles sont dotés d'un seul canal statique. Les médiateurs reliant deux parents consécutifs sont dotés de plusieurs canaux orthogonaux de telle sorte qu'ils peuvent switcher dynamiquement à travers les canaux des parents pour agréger leurs données. Ceci permet la propagation efficace des paquets en parallèle à travers plusieurs canaux de parent à mediateur à parent en direction du sink. Notre approche permet d'obtenir de meilleurs résultats en termes d'interférences, throughput, délai de transmission, routing overhead et d'énergie consommée.

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Chapter 1

Introduction

De nos jours, les Réseaux de Capteurs Sans Fils (RCSFs) peuvent être perçus comme une réalité en raison de l'intégration des systèmes micro-électroniques. La distribution massive d'un grand nombre de capteurs permet de couvrir avec plus de précision un environnement physique. Contrairement à d'autres réseaux comme des Réseaux Mobiles Ad hoc (MANETs), les RCSFs permettent un déploiement dense de capteurs pour effectuer une tâche spécifique. Le déploiement des capteurs est très important puisque la transmission de données est la source première de la consommation en énergie. Le défaut de fonctionnement d'un capteur dû au manque d'énergie peut affecter non seulement le capteur lui-même, mais aussi sa capacité à transmettre les données à d'autres capteurs ou au Sink. Le sink, destinataire final des données, est habituellement connecté à un équipement conventionnel pour les calculs complexes et le traitement des données collectées. La transmission directe des données au sink peut nécessiter une longue distance de transmission et dégrader l'énergie résiduelle des capteurs. Ainsi, il serait intéréssant de traiter localement les données autant que possible pour réduire le nombre de données par capteur à transmettre au sink.

Dans ce chapitre, nous présentons à la Section 1.1 une vue d'ensemble sur les RCSFs. La Section 1.2 définit le problème de recherche et présente notre contribution. La Section 1.3 présente l'organisation du reste de la thèse.

1.1 Réseaux de Capteurs Sans Fils (RCSFs)

Un RCSF comme le montre la Figure 1.1 comprend un grand nombre de capteurs et le sink. Un RCSF peut être défini comme un type de réseau ad hoc sans fil distribué, constitué d'un grand nombre de petits objets appelés capteurs, déployés dans une zone géographique pour collecter les données physiques, climatiques, activités séismiques etc. Les MANETs sont conçus pour faire face aux environnements mobiles. Cependant, ils peuvent aussi être utilisés pour traiter la mobilité dans les RCSFs. [ASSC02] et [WDA10] présentent les principales différences entre RCSFS et MANETs comme suit:

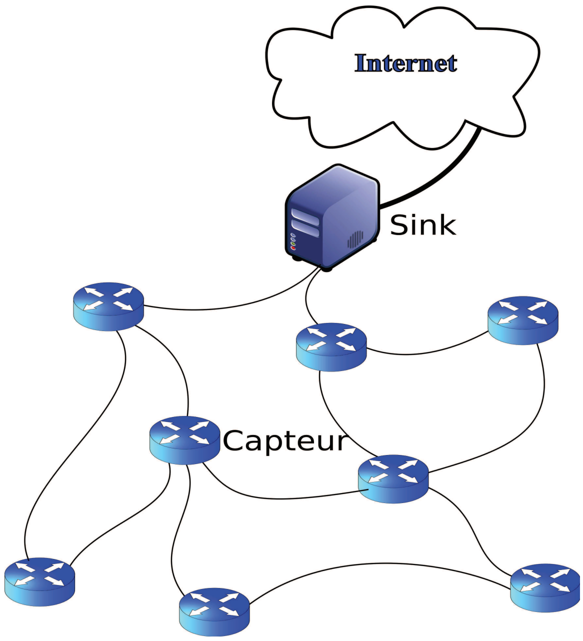

Fig. 1.1: Réseau de capteur sans fil (RCSF)

- Les RCSFs sont destinés pour collecter des informations, tandis que les MANETs sont conçus pour le calcul distribué.
- Dans les MANETs, le routage est fait pour faire face aux environnements mobiles,

tandis que dans les RCSFs, le routage est statique.

- Dans les RCSFs, le nombre de capteurs déployés peut être plus grand que dans les MANETs.

- Les données dans un RCSF sont transmises des capteurs vers le sink, tandis que dans les MANETs, le flux de données est irrégulier.

- L'alimentation et la mémoire de stockage des capteurs peuvent être très limitées en raison de leurs coûts, tandis que les noeuds dans les MANETS (comme des ordinateurs portables) peuvent être rechargés d'une façon ou d'une autre comme décrit par [YMG08].

En tenant compte du modèle de communication, les RCSFs ont des potentiels d'applications dans divers domaines tels que décrit par [SGD+07]: la construction et le contrôle de l'habitat, la gestion de stocks, la détection d'attaque nucléaire, la santé, la gestion des catastrophes, l'agriculture, la détection des feux de brousse, la détection des véhicules, l'armée etc.

1.1.1 Caractéristiques des RCSFs

Certaines caractéristiques des RCSFs sont décrites ci-dessous:

- Taille minuscule: un capteur doit être léger et portable pour réaliser un déploiement commode et à grande échelle. Par exemple, dans les applications médicales, si les capteurs sont plus grands qu'un téléphone portable, ce ne sera pas aisé pour un patient de les porter. Lors du déploiement de capteurs depuis un avion sur plusieurs villes afin de réaliser une surveillance environnementale, plus les capteurs seront grands, moins ils seront facilement déployés.

- Faible coût: les capteurs doivent avoir un coût faible pour les rendre plus adaptés aux différentes applications.

- Faible ressource (énergie, communication, capacité mémoire, bande passante, durée de vie des batteries etc). Dans un RCSF à grande échelle, comme chaque capteur est conçu pour être déployé, nous devons être capables de remplacer chaque batterie de capteurs pour augmenter la durée de vie du réseau.

1.1.2 Architecture générale d'un capteur

Comme le montre la Figure 1.2, l'architecture générale d'un capteur est constituée de quatre modules: collecte, traitement, communication et alimentation.

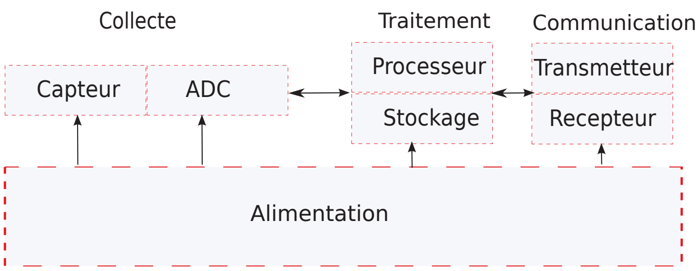

Fig. 1.2: Architecture d'un capteur

- Le module de collecte comporte un Convertisseur d'Analogie à Digitale (ADC) et plusieurs sous-modules pour la collecte environnementale telle que la température, la qualité de l'air etc. Ce module lie le capteur avec le monde extérieur. Pour conserver l'énergie, les capteurs à faible consommation d'énergie doivent s'éteindre s'ils ne sont pas utilisés.

- Le module de traitement inclut un processeur et une mémoire de stockage pour effectuer le traitement local de données. Ce module exécute les opérations de réseau comme la transmission saut-à-saut de données.

- Le module de communication se compose de l'unité de transmission et de reception, qui permet de transmettre et de recevoir les informations collectées à travers le canal sans fil. La transmission de données étant très coûteuse en terme d'énergie, le canal radio doit être éteint s'il n'est pas utilisé.

- Le module d'alimentation permet d'alimenter les capteurs par des batteries ou d'autres sources d'alimentation comme l'énergie solaire etc.

Dans la Section 1.2, nous définissons le problème et présentons notre contribution.

1.2 Définition du problème et Contribution

1.2.1 Définition du problème

Un RCSF est conçu pour collecter les informations et les renvoyer aux utilisateurs via un sink. Dans notre cas (la mesure environnementale), les capteurs inter-agissent avec le monde physique pour collecter les informations. Les données collectées par les capteurs dans une certaine zone doivent être mises à la disposition d'un sink central, qui est le destinataire final des informations collectées. La manière dont les données sont collectées et routées à travers le réseau a un grand impact sur la consommation d'énergie et la durée de vie générale du réseau. [PD07] définissent la durée de vie générale du réseau comme la différence en temps entre le déploiement d'un capteur dans une zone spécifique et le moment où un capteur arrête de fonctionner. L'énergie des capteurs peut être consommée pendant la collecte, le traitement et la communication (transmission et la réception) des données. Comme le montre la Figure 1.3, [Est02] et [KTP+11] ont montré que la transmission de données consomme beaucoup d'énergie. Ainsi, l'énergie d'un capteur constitue le meilleur moyen d'améliorer la performance du réseau. Dans

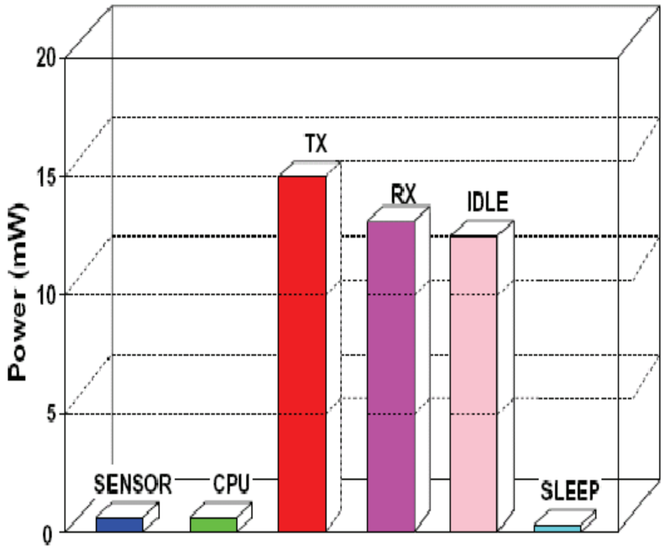

Fig. 1.3: Niveau de consommation d'énergie [Est02]

les RCSFs, tous les capteurs transmettent leur données à un sink central. Dans ce mode de transmission, la transmission de données peut se faire de manière directe ou indirecte. Dans la transmission directe, les capteurs envoient les données directement au sink via un saut. Transmettre les données au sink via un saut peut nécessiter une longue distance de transmission et dégrader ainsi l'énergie résiduelle des capteurs. En cas de transmission indirecte vers le sink, le transfert de données se fait à travers plusieurs sauts offrant ainsi une distance de transmission beaucoup plus courte.

- Du fait de la distance de communication limitée des capteurs, le sink ne peut communiquer qu'avec un certain nombre de capteurs appelés capteurs dans le voisinage du sink, ainsi que le montre la Figure 1.1. Il peut arriver que les capteurs dans le voisinage du sink collectent plus de données parce qu'ils collectent les données d'autres capteurs. Ainsi, la congestion commence à augmenter sur ces capteurs, épuise considérablement les énergies résiduelles de ces derniers et augmente le délai de transmission. La congestion peut être définie comme la situation dans laquelle le volume de données collectées par un capteur devient plus grand que le volume de données qui peuvent être stockées [LSM07].

- Chaque capteur étant équipé d'une capacité de stockage à mémoire limitée, il peut arriver à tout moment, que certains capteurs intermédiaires manquent la réception ou la transmission de nouvelles données vers le sink. Cela cause l'apparition d'une congestion locale dans ces capteurs intermédiaires, augmentant ainsi la quantité de perte de données et affectant la performance globale du réseau.

- Les capteurs peuvent être équipés de plusieurs interfaces radios partageant un seul canal sans fil avec lequel ils peuvent communiquer avec plusieurs voisins. La transmission des données à travers une liaison de communication entre deux capteurs peut interférer avec les transmissions d'autres liaisons si elles transmettent à travers le même canal. En conséquence, l'interférence entre les liaisons et la perte des paquets transmis.

Prenant ensemble toute ces considérations, le problème dans cette thèse est donc de savoir comment réduire le volume de transmission de données des capteurs situé dans le voisinage du sink.

1.2.2 Contributions

La transmission de données étant plus coûteuse en consommation d'énergie que la collecte et le traitement [Est02] et [KTP+11]. Au lieu de minimser le coût de collecte et de traitement, nous proposons de réduire le nombre de transmisisons de chaque capteur afin d'économiser l'énergie pour augmenter la durée de vie du réseau. Dans notre thèse, nous proposons de concevoir une solution complète combinant une technique d'agrégation de données basée sur la construction d'arbres, un routage efficace des données agrégées utilisant des éléments mobile, et une méthode hybride distribuée d'allocation de canaux pour augmenter la durée de vie du réseau.

Concernant l'agrégation de données nous suggérons trois algorithmes d'agrégation de données basée sur la construction d'arbres: Depth-First Search Aggregation ($DFSA$), Flooding Aggregation (FA) and Well-Connected Dominating Set Aggregation ($WCDSA$) comme décrit dans le Chapitre 2. Dans chaque algorithme proposé, les données sont transmises de tous les capteurs vers le sink tout en réduisant le nombre de transmissions de chaque capteur. La transmission de données de chaque capteur vers le sink est faite d'une manière indirecte à travers les capteurs intermédiaires. Un arbre est construit à partir du sink en prenant en compte le degré de connexité de chaque capteur au lieu de l'identité (Id) pour choisir: les capteurs ayant un degré de connexité élevé comme parents (points d'agrégation), et ceux ayant un dégré de connexité faible comme feuilles. Pour transmettre les données, le chemin le plus court entre chaque parent et le sink est extrait via l'algorithme de Dijkstra. Ainsi, les données pourront efficacement être transmises via le chemin le plus court à travers plusieurs sauts de parent à parent vers le sink, réduisant ainsi le nombre de transmissions individuelles par capteur.

Concernant le temps d'agrégation, l'agrégation des données basée sur la construction d'arbres souffre du délai de délivrance de données parce que les parents doivent attendre de recevoir les données de leurs feuilles. Puisque la topologie du réseau peut être déployée aléatoirement, certains parents pourraient avoir beaucoup de feuilles, et il serait alors assez coûteux pour un parent de stocker toutes les données entrantes dans sa mémoire. Ainsi, nous devons déterminer le temps que chaque parent doit mettre pour agréger et traiter les données de ses feuilles, parce qu'il en prend plus pour agréger et traiter les données que pour les transmettre vers le sink. Si un parent attend de recevoir les données de ses feuilles pendant longtemps, il augmente le gain d'agrégation, mais également le temps de délivrance des données au sink. Nous proposons un algorithme, Efficient Tree-based Aggregation and Processing Time (ETAPT) qui utilise la métrique Appropriate Data Aggregation and Processing Time (ADAPT) comme décrit dans le Chapitre 3. Etant donné la durée maximale acceptable, l'algorithme ETAPT prend en compte la position des parents, le nombre de feuilles et la profondeur de l'arbre pour calculer l'ADAPT optimal. Les parents ayant plus de feuilles se verront allouer un ADAPT approprié, afin d'augmenter le gain d'agrégation et de disposer de suffisamment de temps pour traiter les données des feuilles. Les simulations ont été faite pour valider notre algorithme ETAPT. Les résultats obtenus suite aux simulations montrent que notre approche permet d'obtenir un grand gain d'agrégation, une faible consommation en énergie et un temps d'agrégation relativement faible.

Concernant le routage, pendant l'agrégation des données par les parents, il peut arriver que la quantité de données collectées soit très grande et dépasse la quantité de stockage maximale de données que peut contenir leurs mémoires. Pour éviter cela, nous proposons l'introduction dans le réseau de plusieurs collecteurs de données appelés Mini-Sinks (MSs)comme décrit dans le Chapitre 4. Ces MSs sont mobiles et se déplacent selon un modèle de mobilité aléatoire dans le réseau pour maintenir la connectivité afin d'assurer la collecte contrôlée des données basée sur le protocole de routage Mulipath Energy Conserving Routing Protocol (MECRP). Un ensemble de chemins multiples est donc généré entre les MSs et les capteurs pour distribuer le trafic global dans le réseau. Les résultats de simulations ont montré que notre approche permet d'obtenir des résultats meilleurs que les approches existantes. Plusieurs simulations ont été faite pour valider notre approche. Nous avons montré que notre solution permet d'obtenir de meilleurs résultats en termes de pourcentage de paquets délivrés, throughput, end-to-end délai, durée de vie du réseau, énergie résiduelle et overhead.

Concernant l'allocation des canaux, les capteurs peuvent être équipés de plusieurs interfaces radios partageant un seul canal sans fil avec lequel ils peuvent communiquer avec plusieurs voisins. La transmission des données à travers une liaison de communication entre deux parents peut interférer avec les transmissions d'autres liaisons si elles transmettent à travers le même canal. En conséquence, l'interférence entre les liaisons et la perte des paquets transmis. Nous avons besoin de savoir quel canal utiliser en présence de plusieurs canaux pour une transmission donnée Nous proposons une méthode distribuée appelée: Well Connected Dominating Set Aggregation (WCDS-CA) comme décrit dans le Chapitre 5, pour calculer le nombre de canaux qui seront alloués à tous les capteurs de telle sorte que les capteurs adjacents se voient attribués des canaux différents. Dans notre méthode, les parents et les feuilles sont dotés d'un seul canal statique. Les médiateurs reliant deux parents consécutifs sont dotés de plusieurs canaux orthogonaux de telle sorte qu'ils peuvent switcher dynamiquement à travers les canaux des parents pour agréger leurs données. Ceci permet la propagation efficace des paquets en parrallèle à travers plusieurs canaux de parent à mediateur à parent en direction du sink. Les résultats de simulations nous ont montré que notre approche permet d'obtenir de meilleurs résultats en termes d'interférences, throughput, délai de transmission, routing overhead et d'énergie consommée.

1.3 Organisation du reste de la thèse

Le reste de la thèse est organisé en 5 chapitres:

- Le Chapitre 2 présente nos nouveaux algorithmes d'agrégation de données basée sur la construction d'arbres. Le degré de connexité de chaque capteur au lieu de l'identité (Id) pour choisir les capteurs ayant un degré de connexité élevé comme parents, et ceux ayant un dégré de connexité faible comme feuilles. Ainsi, les données pourront efficacement être transmises via le chemin le plus court à travers plusieurs sauts de parent à parent vers le sink, réduisant ainsi le nombre de transmissions individuelles par capteur vers le sink.

- Le Chapitre 3 présente un algorithme Efficient Tree-based Aggregation and Processing Time (ETAPT), pour calculer le temps d'agrégation et de traitement de données. Etant donné la durée maximale acceptable, l'algorithme ETAPT prend en compte la position des parents, le nombre de feuilles et la profondeur de l'arbre. Ainsi, les parents ayant plus de feuilles se verront allouer un temps approprié, afin d'augmenter le gain d'agrégation et de disposer de suffisamment de temps pour traiter les données des feuilles.

- Le Chapitre 4 présente l'introduction des éléments mobiles appelés Mini-Sinks (MSs) dans le réseau pour réduire l'apparition de la congestion. Ces MSs sont mobiles et se déplacent dans le réseau pour maintenir la connectivité afin d'assurer la collecte contrôlée des données basée sur le protocole de routage Mulipath Energy Conserving Routing Protocol (MECRP). Un ensemble de chemins multiples est donc généré entre les MSs et les capteurs pour distribuer le trafic global dans le réseau et réduire la congestion.

- Le Chapitre 5 présente l'allocation efficace des canaux pour réduire les interférences dans le réseau. Une méthode distribuée appelée: Well Connected Dominating Set Aggregation (WCDS-CA), pour calculer le nombre de canaux qui seront alloués à tous les capteurs de telle sorte que les capteurs adjacents se voient attribués des canaux différents. Les parents et les feuilles sont dotés d'un seul canal statique. Les médiateurs sont dotés de plusieurs canaux orthogonaux de telle sorte qu'ils peuvent switcher dynamiquement à travers les canaux des parents pour agréger leurs données.

- Le Chapitre 6 résume nos contributions.

Chapter 2

Agrégation basée sur la structure d'arbres

L'agrégation de données est une technique de conservation d'énergie qui vise à réduire la quantité de données transmises en collectant localement les données par les capteurs intermédiaires afin de transférer les données vers le sink. Dans ce chapitre, nous présentons à la Section 2.1 notre motivation et définissons le problème. Dans la Section 2.2, nous présentons l'environnement de simulations et les résultats comparatifs, puis nous résumons le chapitre à la Section 2.3.

Ce Chapitre est relié à [FE09, FMLE10b, FMLE11b].

2.1 Motivation

Dans le passé, les RCSFs ont été perçus comme une solution alternative pour la communication dans plusieurs domaines techniques comme la mesure environnementale etc [FMLE10a]. Le manque d'infrastructures apporte plusieurs défis dans la conception des techniques de communication pour ces réseaux. Chaque capteur est équipé d'une capacité de stockage limitée; il est capable de communiquer avec ses voisins à travers les connections sans fils. Dans les environnements hostiles où il est souvent difficile de remplacer les batteries des capteurs, l'auto-configuration est recommandée pour maintenir le réseau en fonction aussi longtemps que possible.

Plusieurs techniques pour gérer la transmission de données dans les RCSFs ont été proposées dans la littérature. L'idée de l'agrégation de données est de combiner plus efficacement les données provenant des sources différentes vers le sink. Dans les RCSFs, les données sont généralement collectées par les capteurs dans une zone précise et doivent être transmises à un sink central. Les techniques d'agrégation de données mettent l'accent sur l'agrégation temporelle ou spatiale de données pour réduire leur quantité. Dans l'agrégation temporelle, les données mesurées par les capteurs changent progressivement avec le temps. En considérant l'agrégation spatiale, les données mesurées par les capteurs proches sont similaires. [FLS06] montrent que les capteurs qui utilisent l'agrégation spatiale cherchent la corrélation entre les données reçues pour réduire le flux de données et l'apparition de la congestion. [GP09] démontrent que la réduction du volume de données est connu comme un problème NP-hard. Dans ce travail, nous nous intéressons à l'agrégation spatiale, parce que c'est très important dans le domaine environnemental où les données consécutives mesurées par les capteurs proches ne changent pas beaucoup avec le temps comme décrit dans [SBLC03].

2.1.1 Définition du problème

Considérons une topologie réseau comme le montre la Figure 2.1, constituée de plusieurs capteurs et d'un sink. Tous les capteurs veulent transmettre les données vers le sink à travers les capteurs intermédiaires. Chaque fois qu'un capteur transmet un paquet, son énergie est consommée et sa batterie est déchargée. Chaque capteur mesure périodiquement les données et les transmet au sink via les capteurs intermédiaires. Si la zone de couverture devient très grande, certains capteurs pourraient être distants les

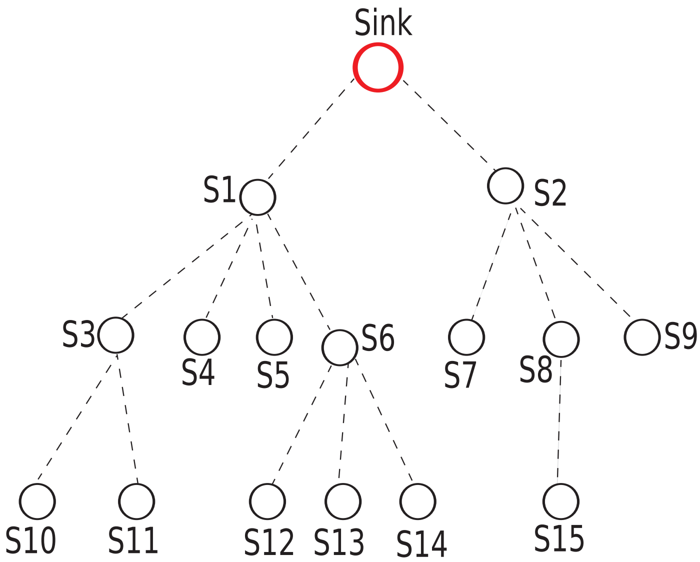

Fig. 2.1: Réseau de capteur sans fil (RCSF)

uns des autres et du sink, et auraient besoin de l'aide des capteurs intermédiaires pour transmettre leur données au sink. A cause de la distance de communication limitée des capteurs, le sink ne peut que communiquer avec un certain nombre de capteurs appelés capteurs dans le voisinage du sink. Il peut arriver que certains capteurs dans le voisinage du sink collectent plus de données parce qu'ils collectent les données des autres. Ainsi, la congestion commence à accroître sur ces capteurs et diminue considérablement leurs énergies résiduelles.

2.1.2 Contribution

Pour résoudre ce problème, nous avons besoin de savoir comment les données sont mesurées par les capteurs et comment elles sont routées à travers le réseau pour pouvoir évaluer l'impact sur la performance du réseau. Notre idée est de réduire le volume de données transmises individuellement par chaque capteur en réduisant le nombre de capteurs intervenant dans la transmission de données. Pour réaliser cela, nous employons la technique d'agrégation. Les capteurs mesurent leurs données consécutives en éliminant les données redondantes et transmettent seulement les données nécéssaires au sink via les capteurs intermédiaires. Nous proposons trois nouveaux algorithmes d'agrégation basés sur la construction d'arbres: Depth-First Search Aggregation (DFSA), Flooding Aggregation (FA) et Well Connected Dominaing Set Aggregation (WCDSA). Nous utilisons la structure d'arbres parce qu'elle est plus adéquate pour les applications comme la mesure des polluants dans l'air, où les données maximales reçues par le sink reflètent les informations les plus utiles. Dans chaque algorithme proposé, un arbre est construit à partir du sink comme le montre la Figure 2.2, en prenant en compte le dégré de connexité de chaque capteur pour choisir:

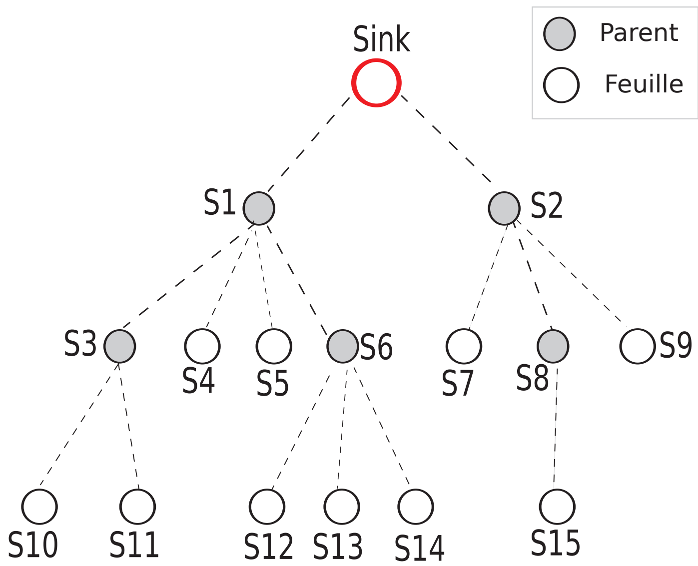

Fig. 2.2: Réseau de capteur sans fil (RCSF)

- Les capteurs ayant un dégré de connexité élevé comme parents et ceux ayant un dégré de connexité faible comme feuilles.

- Le chemin le plus court entre chaque parent et le sink, extrait via l'algorithme de Dijkstra.

Ainsi, les données pourront efficacement être transmises via le chemin le plus court à travers plusieurs sauts de parent à parent vers le sink, réduisant ainsi le nombre de transmissions individuelles de données de chaque capteur.

2.2 Environnement de simulations et résultats comparatifs

2.2.1 Environnement de simulations

Nous avons analysé chaque algorithme avec un nombre de capteurs variant entre [50-500] dans une zone de 1000m x 1000m. L'implémentation a été faite avec le simulateur SCILAB. La connexion existe entre deux capteurs s'ils sont distants d'au moins 30m. Pour valider notre analyse, nous avons répété 10 fois les expériences avec la même topologie de 90% d'intervalle de confiance entre chaque données. La valeur moyenne de ces résultats est présentée ci-dessous.

Puisque le sink est le destinataire final des données mesurées, sa position est cruciale pour recevoir efficacement les données. L'objectif est d'étudier l'effet de la position du sink pendant l'agrégation des données. Dans notre analyse, nous supposons que chaque capteur dans le réseau peut être le sink. Pour chaque position du sink, nous sélectionnons la meilleure position pour obtenir le nombre minimum de paquets transmis au sink, et le nombre maximum de feuilles dans le réseau.

2.2.2 Résultats comparatifs

Plusieurs simulations ont été faites avec quelques algorithmes existants comme Depth-First Search (DFS), Breadth-First Search (BFS). Les résultats nous ont montré que le nombre minimum de paquets transmis au sink et le nombre maximum de feuilles dans chaque algorithme varient pour chaque position du sink choisi. Pour toutes les positions du sink choisies, WCDSA présente de meilleurs résultats que BFS, FA, DFSA et DFS respectivement.

2.3 Résumé

Dans ce chapitre, nous avons présenté trois nouveaux algorithmes d'agrégation basés sur la construction d'arbres: Depth-First Search Aggregation (DFSA), Flooding Aggregation (FA) et Well Connected Dominating Set Aggregation (WCDSA). Ces algorithmes ont pour but de réduire le nombre de transmissions de chaque capteur vers le sink. Dans chaque algorithme proposé, un arbre est construit à partir du sink en prenant en compte le degré de connexité de chaque capteur pour choisir les capteurs ayant un degré de connexité élevé comme parents et ceux ayant un degré de connexité faible comme feuilles. Le chemin le plus court entre chaque parent et le sink est établi par l'algorithme de Dijkstra. Ainsi, les données pourront être transmises via le chemin le plus court à travers plusieurs sauts de parent à parent vers le sink en réduisant ainsi le nombre de transmissions individuelles de chaque capteur. La position du sink étant cruciale pour la réception des données, pour chaque position du sink dans le réseau, nous sélectionnons la meilleure position pour obtenir le nombre minimum de paquets transmis au sink et le nombre maximum de feuilles dans le réseau.

Dans le chapitre suivant, nous proposons un nouveau algorithme Efficient Tree-based Aggregation and Processing Time (ETAPT), pour calculer le temps d'agrégation et de traitement de données des feuilles par les parents.

Chapter 3

Temps approprié d'agrégation et de traitement de données

Dans le Chapitre 2, nous avons vu que l'agrégation de données pourrait être une technique efficace de conservation de l'énergie en réduisant le nombre de transmissions individuelles de chaque capteur dans le réseau. Puisque le sink doit recevoir les données de tous les capteurs, il est important de transmettre les données à temps vers le sink. Dans ce chapitre, nous présentons dans la Section 3.1 notre motivation et formulons le problème. Dans la Section 3.2, nous présentons les critères de performances et les résultats comparatifs. Dans la Section 3.3, nous résumons le chapitre.

Ce chapitre est relié à [FMLE10b, FMLE11b, FLE13].

3.1 Motivation

Dans les RCSFs, chaque capteur couvre une zone définie, collectant les données et les transférant vers le sink. Comme le sink doit recevoir les données des capteurs à temps, l'agrégation de données est en étroite relation avec le temps d'agrégation et de traitement. Ainsi, après avoir construit l'arbre pour transmettre les données comme décrit dans le chapitre précédent, il est impératif de considérer le temps mis par les parents pour agréger et de traiter les données de leurs feuilles. En effet, cela prend beaucoup plus de temps d'agréger et traiter les données que de les transmettre vers le sink. La promptitude de la délivrance des données au sink aboutit à une meilleure performance du réseau.

3.1.1 Formulation du problème

Dans notre contexte (agrégation spatiale), les données mesurées par les capteurs proches sont similaires. L'agrégation des données est retardée par le délai de transmission de celles-ci car les parents doivent attendre de recevoir les données de leurs feuilles. Comme la topologie du réseau peut être déployée aléatoirement, certains parents dans l'arbre pourraient avoir beaucoup de feuilles comme le montre la Figure 3.1. Il serait assez

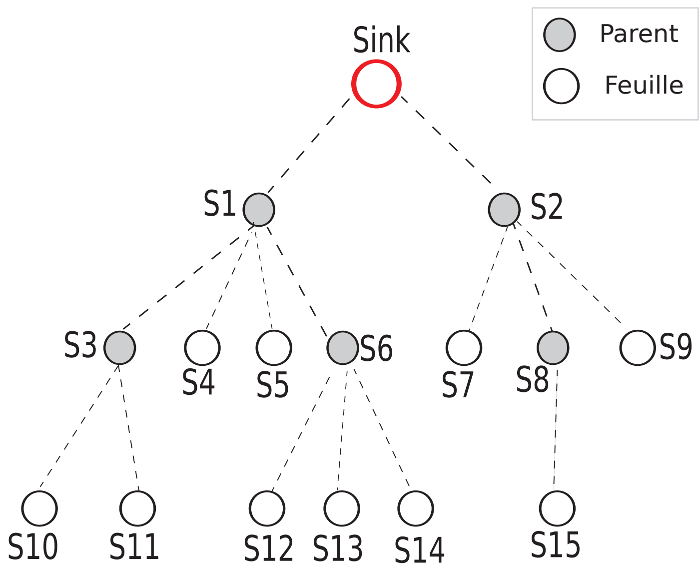

Fig. 3.1: Réseau de capteur sans fil (RCSF)

coûteux pour un parent de stocker toutes les données entrantes dans sa mémoire. Si un parent attend de recevoir les données de ses feuilles pendant longtemps, il accroît le gain d'agrégation, mais cependant augmente le temps de délivrance des données au sink. Ainsi, il est important de considérer le temps que chaque parent doit mettre pour agréger et traiter les données de ses feuilles. Négliger ce temps d'agrégation peut augmenter le temps de délivrance des données au sink ou réduire le gain d'agrégation.

Le problème soulevé ici est celui de la détermination du temps d'agrégation que chaque parent doit effectuer dans l'arbre pour agréger et traiter les données de ses feuilles.

3.1.2 Contribution

Pour résoudre ce problème, nous proposons un nouvea algorithme, Efficient Tree-based Data Aggregation and Processing Time (ETAPT), qui permet de s'assurer que le temps d'agrégation et de traitement de données par les parents est approprié. Après avoir construit un arbre comme le montre la Figure 3.2.

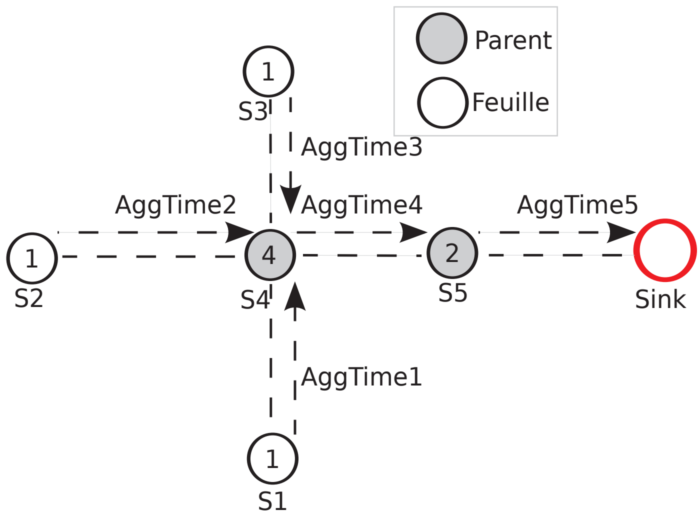

Fig. 3.2: Distribution du temps d'agrégation

Etant donné la durée maximale acceptable, l'algorithme ETAPT prend en compte:

- la position des parents;
- le nombre de feuilles;
- la profondeur de l'arbre.

Ainsi, les parents ayant plus de feuilles se verront allouer un temps approprié, afin d'augmenter le gain d'agrégation et de disposer de suffisamment de temps pour traiter les données des feuilles.

3.2 Critères de performances et résultats comparatifs

3.2.1 Critères de performances

Nous avons implémenté nos algorithmes sous Qualnet avec un nombre de capteurs variant entre [100 - 500] dans une zone de 1000m x 1000m. La connexion existe entre deux capteurs s'ils sont distants d'au plus 20m. Pour valider notre analyse, nous avons répété 20 fois les analyses avec la même topologie. La valeur moyenne de ces résultats est présentée içi. Le sink est placé au coin en haut et à gauche de la zone de couverture. Pendant l'exécution de nos simulations, une source donnée et une destination sont considérées jusqu'à ce que la communication entre elles s'arrête en raison de l'épuisement d'énergie. Au début des simulations, chaque capteur avait une batterie contenant une énergie de 10^4 Joules. Nous avons considéré la durée maximale acceptable variant entre [3, 4, 5, 6]s, afin d'étudier: le gain d'agrégation, l'énergie consommée et le temps d'agrégation.

3.2.2 Résultats comparatifs

Plusieurs simulations ont été faites et les résultats sont comparés avec deux techniques proches de la nôtre: Data Aggregation Supported by Dynamic Routing (DASDR) [ZWR$^+$10] et Aggregation Time Control (ATC) [CLL$^+$06]. Les analyses nous ont montré que notre approche présente de meilleurs résultats que DASDR et ATC avec un pourcentage de gain d'agrégation d'environ 90%, comparé à 84% pour DASDR et 73.5% pour ATC.

Concernant la consommation en énergie, nous constatons que notre approche réduit d'environ 34.78% et 67.22% la consommation en énergie dans DASDR et ATC respectivement. Pour évaluer le temps d'agrégation, nous avons fait varier la distance de communication entre $[20, 30, 40, 50, 60]$m. Nous constatons que le temps d'agrégation diminue dans chacune des trois méthodes. Ceci est dû au fait qu'augmenter la distance de communication crée un réseau déconnecté dans lequel certains capteurs ne sont pas connectés. Par conséquent, cela diminue le dégré de connexité des parents et réduit le temps d'agrégation de chaque parent. Lorsque nous varions la profondeur du réseau de $[3, 4, 5, 6]$, en gardant constant le temps d'agrégation, nous constatons que le temps d'agrégation augmente aussi. Ceci est dû au fait que les parents appartenant à l'arbre auront besoin de beaucoup plus de temps pour agréger les données de leurs feuilles. Dans tous les cas, notre approche permet de réduire le temps d'agrégation d'environ 17% dans DASDR et 40% dans ATC.

3.3 Résumé

Dans ce chapitre, nous avons vu un nouveau algorithme: Efficient Tree-based Data Aggregation and Processing Time (ETAPT), qui permet de s'assurer que le temps d'agrégation et de traitement de données par les parents est approprié. Etant donné la durée maximale acceptable, le calcul de l'ETAPT prend en compte la position des parents, le nombre de feuilles et la profondeur de l'arbre. Ainsi, les parents ayant plus de feuilles seront dotés dynamiquement d'un temps d'agrégation approprié, afin d'augmenter le gain d'agrégation et de donner suffisamment de temps pour traiter les données de leurs feuilles. Les résultats obtenus suite aux simulations montrent que notre approche permet d'obtenir un grand gain d'agrégation, une faible consommation en énergie et un temps d'agrégation relativement faible comparé à [ZWR+10] et [CLL+06].

Dans le chapitre suivant, nous proposons l'introduction dans le réseau d'éléments mobiles afin de réduire l'apparition de la congestion due à la capacité de stockage limitée des capteurs.

Chapter 4

La mobilité des mini-sinks pour réduire la congestion

La mobilité du sink peut être vue comme une solution appropriée pour réduire l'apparition de la congestion dans les RCSFs. Dans ce chapitre, nous présentons dans la Section 4.1, notre motivation et formulons le problème. Dans la Section 4.2, nous présentons les critères de performances et les résultats comparatifs. Dans la Section 4.3, nous résumons le chapitre.

Ce chapitre est relié à [FMLE10a, FMLE11c, FLE12b, FLE12a, FLE12d].

4.1 Motivation

Le manque d'infrastructures prédéfinies apporte plusieurs défis dans la conception des techniques de communication pour les RCSFs, où il est souvent difficile de remplacer les batteries des capteurs après déploiement. Comme tous les capteurs collectent et transfèrent les données à d'autres capteurs ou au sink, l'auto-configuration est recommandée pour donner la possibilité à tous les capteurs de transférer efficacement les données afin d'améliorer la performance du réseau [CT04]. Dans la plupart des applications, les capteurs sont statiques, permettant le transfert de données d'une manière réactive. Par contre, [WT09] ont montré que le déploiement statique des capteurs a plusieurs inconvénients comme la connexité limitée: en effet, le déploiement des capteurs statiques peut ne pas garantir la connexité globale de tout le réseau. Ainsi, le réseau peut être partitionné en plusieurs sous-réseaux non connectés. Les capteurs étant alimentés par les batteries, certains capteurs s'éteindront en raison de l'épuisement de leur batteries, affectant certainement la performance globale du réseau.

4.1.1 Définition du problème

Dans les RCSFs, comme le montre la Figure 4.1, chaque capteur est équipé d'une capacité de stockage de mémoire limitée. A n'importe quel moment, certains capteurs intermédiaires manqueront de recevoir ou de transmettre de nouvelles données vers le sink, parce que le volume de données collectées devient plus grand que le volume de données qui peuvent être stockées. Cela cause l'apparition de la congestion locale dans ces capteurs intermédiaires, augmentant donc la quantité de perte de données, et affectant la performance globale du réseau.

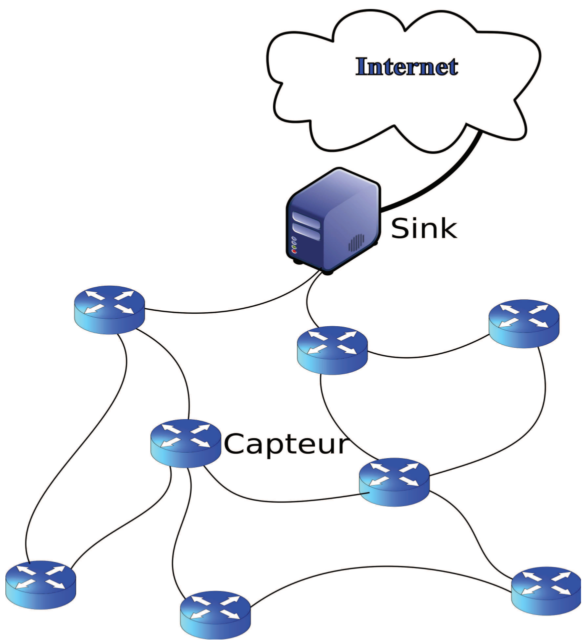

Fig. 4.1: Réseau de capteur sans fil (RCSF)

Le problème soulevé ici est celui de la diminution du volume de données transférés par les capteurs dans le réseau.

4.1.2 Contribution

Une technique pour résoudre ce problème est d'introduire dans le réseau certains éléments mobiles de collecte de données afin de réduire l'apparition de la congestion. Dans notre approche, au lieu d'avoir un sink central responsable de la collecte des données, nous introduisons plusieurs mini-collecteurs de données appelés Mini-Sinks (MSs) comme le montre la Figure 4.2. Dans notre configuration:

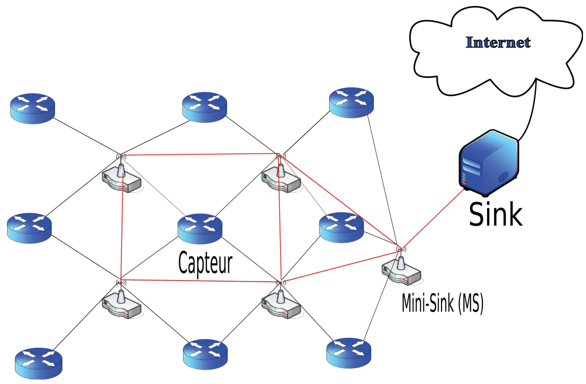

Fig. 4.2: Réseau de capteurs avec mini-sink

- Les capteurs et le sink sont fixes, mais les MSs sont mobiles.
- Ces MSs se déplacent selon un modèle de mobilité aléatoire dans le réseau pour maintenir la connexité globale et assurer la collecte contrôlée de données basée sur le protocole de routage Multipath Energy Conserving Routing Protocol (MECRP).
- MECRP est implémenté entre les capteurs et les MSs pour optimiser le coût de transmission.

- Un ensemble de chemins multiples est généré entre les MSs et les capteurs pour distribuer le trafic global dans le réseau.

Ainsi, négligeant l'exigence sur la connexité du réseau, l'apparition de la congestion dans le réseau pourrait être réduite afin d'améliorer significativement la performance du réseau et rendant notre approche adéquate pour les réseaux denses.

4.2 Environnement de simulations et résultats comparatifs

4.2.1 Environnement de simulations

Nous avons implémenté notre topologie réseau en utilisant le simulateur Qualnet. La topologie est décrite par le nombre de capteurs statiques appartenant au réseau et leurs positions. Dans toutes nos analyses, nous avons déployé 100 capteurs statiques dans un espace géographique L. Le sink est placé au coin à gauche de la zone L. Chaque capteur peut transmettre un certain nombre de données à un MS qui présente un coût faible avant l'épuisement total de son énergie. Les MSs de déplacent avec une vitesse variant entre [0....10]mps. Pendant l'exécution de nos simulations, une source et une destination sont considérées durant les évaluations. Initialement, chaque capteur a une énergie de 10^4 Joules. Un capteur est considéré non-fonctionnel si son énergie atteint la valeur de 0. Nous avons repété 100 fois les analyses avec une même topologie; la valeur moyenne est reportée içi.

4.2.2 Critères de performances

Pour un réseau bien défini, l'ECRP est appliqué entre un capteur selectionné et un MS proche. Nous rappelons que dans le cas de l'utilisation d'un sink unique et d'un sink mobile comme décrit dans [CKN06], un seul paquet est transmis entre une paire de capteur (S_i, S_j). Dans notre cas, comme plusieurs chemins sont utilisés pour le routage de données, nous supposons que plusieurs paquets sont transmis entre chaque paire de capteur (S_i, S_j) jusqu'à ce que la configuration du réseau change. Nous avons utilisé les simulations pour évaluer:

- Le nombre de MSs qui devraient être utilisés pour avoir une connexité globale du réseau.
- Le nombre de chemin multiples que devraient utiliser chaque capteur pour transmettre efficacement les données.
- Le pourcentage des paquets délivrés suite à la mobilité des MSs.
- Le End-to-End délai dû à la mobilité des MSs.
- L'effet de la longueur de la session sur la durée de vie et l'énergie résiduelle globale du réseau.
- L'effet du rayon de localité sur la durée de vie et l'énergie résiduelle globale du réseau.
- L'effet de la densité du réseau sur la durée de vie et l'énergie résiduelle globale du réseau.

4.2.3 Résultats comparatifs

Les résultats des simulations montrent que la capacité de connexité du réseau augmente quand le nombre de MSs augmente. La connexité globale du réseau peut être obtenue avec au moins 25 MSs pour un réseau contenant 100 capteurs. Concernant le pourcentage de paquets délivrés au sink, les analyses montrent que l'approche utilisant un sink fixe présente le plus petit pourcentage de paquets délivrés au sink que [CKN06] et notre approche. Ceci est dû au fait que dans l'approche utilisant un sink fixe, la transmission de données est faite par plusieurs capteurs intermédiaires et certains capteurs intermédiaires manqueront la réception ou la transmission de données ce qui diminuera le pourcentage de données reçues par le sink. Notre approche permet d'obtenir un meilleur pourcentage de paquets avec environ 95.5%, comparé à 88.55% pour [CKN06] et 75.75% pour le sink statique. Dans le cas de [CKN06], la mobilité du sink permet de réduire l'utilisation des capteurs intermédiaires pendant la transmission des données au sink. Les résultats de l'évolution du throughput en fonction de la vitesse des MSs montrent que le throughput diminue quand la vitesse des MSs augmente. Ceci est dû au fait que les capteurs n'auront pas suffisamment du temps pour calculer les coûts des chemins pour choisir les MSs ayant un faible coût avant de transmettre les données. Quand la vitesse des MSs varie entre $[2.5 - 10]$mps, notre approche présente de meilleurs résultats que Ioannis et al. et le cas du sink fixe avec un pourcentage d'environ 11.24% et 35.94% respectivement. Nous avons constaté qu'en augmentant la vitesse des MSs, nous obtenons un end-to-end délai moins important que [CKN06] et l'approche du sink statique. Ceci parce que la mobilité permet de moins utiliser les requêtes pour la recherche des routes lors de la transmission de données.

4.3 Résumé

Dans ce chapitre, nous avons proposé l'utilisation de plusieurs MSs, au lieu d'un seul sink statique pour la collecte de données. Plusieurs MSs sont mobiles et se déplacent selon un modèle de mobilité arbitraire dans le réseau afin de maintenir la connexité globale et assurer la collecte contrôlée de données basée sur le protocole de routage MECRP. Un ensemble de chemins multiples est généré entre les MSs et les capteurs pour distribuer le trafic global dans le réseau. Ainsi, négligeant l'exigence sur la connexité du réseau, l'apparition de la congestion dans le réseau pourrait être réduite afin d'améliorer significativement la performance du réseau. Nous avons comparé les résultats avec l'approche utilisant un sink statique et un sink mobile proposé par [CKN06]. Les conclusions montrent que notre solution permet d'obtenir de meilleurs résultats en termes de pourcentage de paquets délivrés, throughput, end-to-end délai, durée de vie du réseau, énergie résiduelle et overhead.

Dans le chapitre suivant, nous proposons l'allocation des canaux multiples dans les interfaces radios pour réduire l'apparition des interférences pendant la transmission de données.

CHAPTER 5

Allocation des canaux multiples dans les interfaces radios

L'apparition des interférences pendant la transmission de données affecte la performance des RCSFs. Dans ce chapitre, nous présentons à la Section 5.1 notre motivation et définissons le problème. A la Section 5.2, nous présentons les critères de performances et les résultats comparatifs. La Section 5.3 résume le chapitre.

Ce chapitre est relié à [FMLE10b, FMLE11a, FLE12c, FLZE13].

5.1 Motivation

Dans les Chapitres 2 et 3, nous avons proposé l'agrégation de données utilisant la structure d'arbres dans laquelle les données collectées étaient transmises de parent à parent vers le sink en réduisant le nombre de transmissions individuelles de chaque capteur. Les capteurs peuvent être équipés de plusieurs interfaces radios partageant un seul canal sans fil avec lequel ils peuvent communiquer avec plusieurs voisins. Pendant la transmission des données, une allocation efficace des canaux parmi les capteurs pourrait réduire les interférences. [L0́7] montrent que calculer le nombre minimum de canaux nécéssaires attribuer à tous les capteurs dans le réseau est un problème NP-Hard. Nous proposons une méthode distribuée appelée: Well Connected Dominating Set Aggregation (WCDS-

CA), pour calculer le nombre de canaux qui seront alloués à tous les capteurs de telle sorte que les capteurs adjacents se voient attribués des canaux différents.

5.1.1 Définition du problème

Considérons un RCSF constitué de N capteurs, dans lequel chaque capteur pourrait être équipé de plusieurs interfaces radios partageant un seul canal sans fil qu'il utilise pour communiquer avec plusieurs voisins. La transmission des données à travers une liaison de

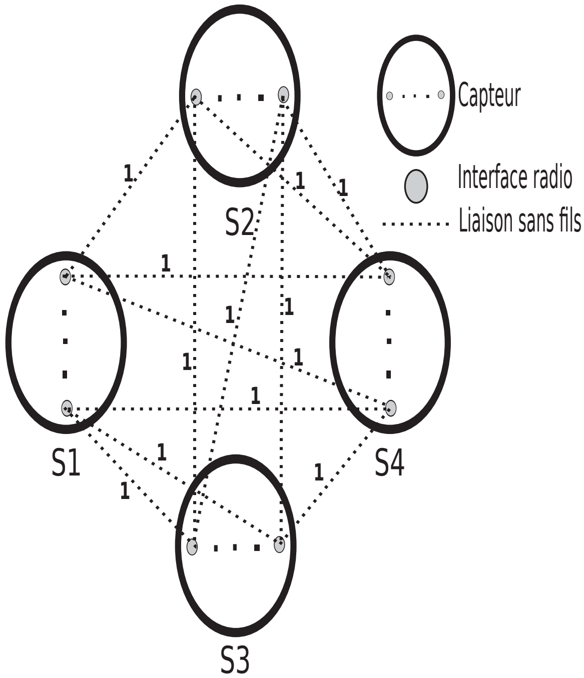

Fig. 5.1: Transmission à travers un canal

communication entre deux parents peut interférer avec les transmissions d'autres liaisons si elles transmettent à travers le même canal. Deux liaisons (i, j) et (i', j') interfèrent si elles transmettent dans le même canal au même moment. Ainsi, l'interférence peut être définie comme l'ensemble des liaisons qui peuvent interférer avec n'importe quelle autre dans le réseau.

Considérons un réseau constitué de quatre capteurs $S_i, ..., S_n$ pour $(i = 1, .., 4)$. Chaque capteur est équipé de plusieurs interfaces radios représentées par des petits cercles, tandis que les liaisons sont représentées par des pointillés. Chaque liaison est identifiée par son numéro de canal. La Figure 5.1 montre un réseau dans lequel tous les capteurs utilisent le canal 1 au même moment. La transmission des données ne peut pas être réalisée entre les paires de capteurs parce que tous transmettent à la fois sur le même canal. En conséquence, l'interférence entre les liaisons et la collision des paquets transmis à travers le canal apparaît et affecte la performance du réseau.

Le problème posé ici est de savoir quel canal utiliser en présence de plusieurs canaux pour une transmission donnée.

5.1.2 Contribution

Pour résoudre ce problème, nous proposons une méthode distribuée d'allocation de canaux comme le montre la Figure 5.2. Nous allouons un canal unique dans le réseau

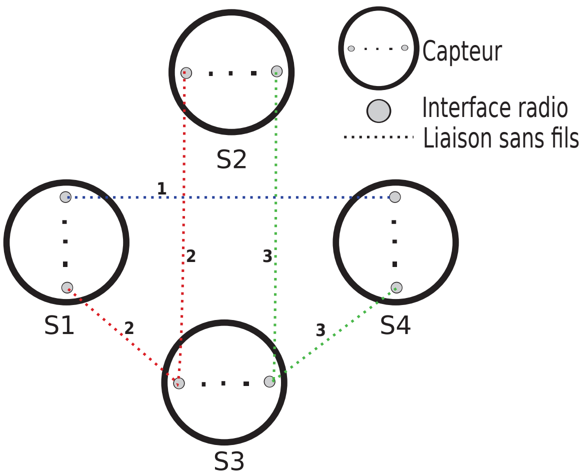

Fig. 5.2: Allocation distribuée des canaux

à chaque interface radio de telle sorte que le nombre de canaux distincts alloués aux liaisons adjacentes d'un capteur donné est au plus égal au nombre d'interfaces radios de ce capteur. Les parents et les feuilles sont dotés d'un seul canal statique. Les médiateurs reliant deux parents consécutifs sont dotés de plusieurs canaux orthogonaux de telle sorte qu'ils peuvent switcher dynamiquement à travers les canaux des parents pour collecter leurs données.

5.2 Critères de performances et résultats comparatifs

5.2.1 Environnement de simulations

Nous avons évalué les performances de notre méthode WCDS-CA à travers plusieurs simulations sous MATLAB. Nous avons utilisé un nombre de capteurs variant entre $[50 - 400]$. Dans nos analyses, le nombre de canaux variait entre $[1 - 4]$, tandis que le nombre de liaisons radios variait entre $[2 - 10]$. Nous avons considéré un réseau de 184 capteurs, avec 498 liaisons, où 42 parents sont choisis en tenant compte de leur dégré de connexité. Les médiateurs liant deux parents sont choisis. Le sink, choisi aléatoirement parmi les parents, est placé au coin à gauche de la zone de couverture L. Chaque capteur dans le réseau génère un paquet chaque 3s. Nous avons repété 20 fois les analyses avec la même topologie, la valeur moyenne est reportée ci-dessous. Pour évaluer l'efficacité de notre méthode, nous l'avons comparée avec deux approches proposées précédemment: l'une utilisant un seul canal et l'autre appelée Sensor Multi-Channel Medium Access Control (SMC MAC) [RR09]. Les critères de performances suivants ont été évalués: interférence, sink throughput, délai de transmission, routing overhead et energie consommée.

5.2.2 Résultats comparatifs

Les résultats des analyses montrent que quand le nombre de canaux augmente, le nombre maximum de liaisons communes (interférences) utilisées par chaque capteur diminue. Nous observons aussi l'augmentation du throughout lorsque le nombre d'interfaces radios et de canaux augmente dans les trois cas comme le montre la Table 5.1. Nous constatons que notre méthode permet d'obtenir de meilleurs résultats que SMC MAC et l'approche utilisant un seul canal dû à l'allocation hybride des canaux.

Table 5.1: Throughput avec un canal, SMC MAC, et WCDS-CA

Méthodes	Un canal	SMC MAC	WCDS-CA	Amélioration de SMC MAC par rapport à un canal	Amélioration de WCDS-CA par rapport à un canal	Amélioration de WCDS-CA par rapport à SMC MAC
Throughput	46%	86%	96%	46.15%	51.72%	10.35%

Quand le nombre de canaux augmente de $[2-4]$, le délai de transmission diminue dans notre approche et dans celle de SMC MAC; mais pas dans l'approche d'un seul canal. Les résultats similaires sont observés lorsque la densité du réseau varie de $[50-400]$ capteurs. Concernant l'évolution de l'énergie consommée, nous constatons dans les trois approches que l'énergie utilisée pour transmettre les données à travers un seul canal est constante d'environ 45mJ. Avec la variation des canaux, l'énergie diminue considérablement dans WCDS-CA et SMC MAC. Ceci est dû à la transmission parallèle de données à travers plusieurs canaux. La Table 5.2 présente les statistiques de l'évolution de la consommation en énergie. Nous constatons que notre approche permet de réduire l'énergie consommée maximale d'environ 77%, SMC MAC d'environ 60% et le canal unique d'environ 15%.

Table 5.2: Energie consommée avec un canal, SMC MAC, et WCDS-CA

Méthodes	Un canal	SMC MAC	WCDS-CA	Amélioration de SMC MAC par rapport à un canal	Amélioration de WCDS-CA par rapport à un canal	Amélioration de WCDS-CA par rapport à SMC MAC
Energie maximale consommée (mJ)	45 mJ	45 mJ	45 mJ	0 mJ	0 mJ	0 mJ
Energie maximale consommée (mJ)	38 mJ	18 mJ	10 mJ	20 mJ	28 mJ	8 mJ
Diminution de l'énergie consommée (%)	15%	60%	77%	52.63%	73.68%	44.44%

5.3 Résumé

Dans ce chapitre, nous avons présenté une méthode distribuée d'allocation des canaux dans les RCSFs. Les parents et les feuilles sont dotés d'un seul canal statique. Les médiateurs sont dotés de plusieurs canaux orthogonaux de telle sorte qu'ils peuvent switcher dynamiquement à travers les canaux des parents pour collecter les données. Nous avons montré que notre approche permet d'obtenir de meilleurs résultats que [RR09] et l'approche utilisant un seul canal en termes d'interférences, throughput, délai de transmission, routing overhead et d'énergie consommée.

Dans le chapitre suivant, nous résumons les contributions présentées dans cette thèse.

Chapter 6

Conclusion

Les RCSFs sont utilisés pour collecter les données et les renvoyer aux usagers via le sink. Dans les RCSFs, chaque capteur est équipé d'une batterie limitée et communique avec ses voisins à travers les liaisons sans fils. Quand deux capteurs transmettent les données, ils utilisent leurs énergies pendant la transmission. Dans notre cas, les capteurs inter-agisssent avec le monde physique pour collecter les informations à travers certaines zones et les mettent à la disposition d'un sink central qui est le destinataire final pour le traitement. Nous nous sommes intéréssés à la manière dont les données sont transmises dans le réseau parce que la transmission des données consomme beaucoup plus d'énergie que leur traitement et leur collecte. Nous avons proposé de réduire le nombre de transmissions de chaque capteur vers le sink afin d'améliorer la performance du réseau. Dans les sections suivantes, nous résumons les différentes contributions.

6.1 Agrégation utilisant la structure d'arbres

Dans le Chapitre 2, nous avons suggéré trois nouveaux algorithmes d'agrégation basés sur la structure d'arbres: Depth-First Search Aggregation (DFSA), Flooding Aggregation (FA) et Well Connected Dominating Set Aggregation (WCDSA). Ces algorithmes ont pour but de réduire le nombre de transmissions de chaque capteur vers le sink. Dans chaque algorithme proposé, un arbre est construit à partir du sink en prenant en compte le degré de connexité de chaque capteur pour choisir les capteurs ayant un degré de connexité élevé comme parents, et ceux ayant un dégré de connexité faible comme feuilles. Le chemin le plus court entre chaque parent et le sink est établi avec l'algorithme de Dijkstra. Ainsi, les données pourront être transmises via le chemin le plus court à travers plusieurs sauts de parent à parent vers le sink, réduisant ainsi le nombre de transmissions individuelles de chaque capteur. La position du sink est cruciale pour la réception de données. Nous sélectionnons la meilleure position du sink pour obtenir le nombre minimum de paquets transmis au sink et le nombre maximum de feuilles. Pour toutes les positions du sink choisies, WCDSA présente de meilleurs résultats que BFS, FA, DFSA et DFS respectivement. Les avantages et inconvénients peuvent être résumté dans le Tableau 6.1.

	DFS	BFS	DFSA	FA	WCDSA
Critères	Noeud Id	Noeud Id	Noeud degré	Noeud niveau de congestion	Noeud degré
Topologie	Régulière	Régulière	Irrégulière	Irrégulière	Irrégulière
Performance	Nombre de relais	Nombre de relais	Nombre de transmissions et de feuilles	Nombre de transmissions et de feuilles	Nombre de transmissions et de feuilles
Avantages	Pas de connaissance globale	Pas de connaissance globale	Diminution du flux, augmentation de la durée de vie	Diminution du flux, augmentation de la durée de vie	Diminution du flux, augmentation de la durée de vie
Inconvénients	Pas d'économie d'énergie	Pas d'économie d'énergie	Pas de résistance à la défaillance des noeuds	Pas de résistance à la défaillance des noeuds	Pas de résistance à la défaillance des noeuds

Table 6.1: Comparaison

6.2 Temps approprié d'agrégation et de traitement de données

Au Chapitre 2, nous avons vu que l'agrégation des données pourrait être une technique efficace de conservation de l'énergie en réduisant le nombre de transmissions individuelles de chaque capteur dans le réseau. Les données collectées par les parents pourraient souffrir de l'augmentation du délai de transmission de données au sink, parce que les parents doivent attendre de recevoir les données des feuilles avant de les transmettre au sink. Comme le sink doit recevoir les données de tous les parents, il est important de transmettre les données à temps vers le sink. Au Chapitre 3, nous avons proposé une nouvelle métrique, Appropriate Data Aggregation and Processing Time (ADAPT). Etant donné la durée maximale acceptable, le calcul de l'ADAPT prend en compte la position des parents, le nombre de feuilles et la profondeur de l'arbre. Ainsi, les parents ayant plus de feuilles seront dotés dynamiquement d'un temps d'agrégation approprié, pour augmenter le gain d'agrégation et assurer suffisamment de temps pour traiter les données de leurs feuilles. Les résultats obtenus lors des simulations montrent que notre approche permet d'avoir un gain d'agrégation et un pourcentage de paquets délivrés élevé, avec une faible consommation en énergie et un temps d'agrégation relativement faible comparé à [ZWR+10] et [CLL+06].

6.3 Mobilité des mini-sinks pour réduire la congestion

Nous avons vu aux Chapitres 2 et 3 que l'agrégation des données utilisant la structure d'arbres est une technique efficace de conservation d'énergie. Chaque capteur est équipé d'une capacité de stockage à mémoire limitée: pendant la transmission de données, certains capteurs intermédiaires manqueront de recevoir ou de transmettre de nouvelles données vers le sink, parce que le volume de données collectées devient plus grand que le volume de données qui peuvent être stockées; cela cause l'apparition de la congestion locale dans ces capteurs intermédiaires, augmentant ainsi la quantité de données perdues, et affectant la performance globale du réseau. Nous avons proposé au Chapitre 4, l'introduction de plusieurs MSs, au lieu d'un seul sink statique pour la collecte de données. Plusieurs MSs sont mobiles et se déplacent selon un modèle de mobilité arbitraire dans le réseau pour maintenir la connexité globale et assurer la collecte contrôlée de données basée sur le protocole de routage MECRP. Un ensemble de chemins multiples est généré entre les MSs et les capteurs pour distribuer le trafic global dans le réseau. Ainsi, négligeant l'exigence sur la connexité du réseau, l'apparition de la congestion dans le réseau pourrait être réduite afin d'améliorer significativement la performance du réseau. Nous avons comparé les résultats avec l'approche utilisant un sink statique et un sink mobile [CKN06]. Les résultats montrent que notre solution permet d'obtenir de meilleurs résultats en termes de pourcentage de paquets délivrés, throughput, end-to-end délai, durée de vie du réseau, énergie résiduelle et overhead.

6.4 Allocation des canaux multiples dans les interfaces

Pendant l'agrégation des données comme présentée aux Chapitres 2 et 3, la transmission des données à travers une liaison de communication entre deux parents peut interférer avec les transmissions d'autres liaisons si elles transmettent à travers le même canal. Nous nous sommes intéressé au choix du canal à utiliser en présence de plusieurs canaux pour une transmission de données. Pour ce faire, nous avons proposé une méthode hybride distribuée d'allocation de canaux appelée Well Connected Dominating Set Aggregation (WCDS-CA) dans laquelle, nous attribuons un canal unique dans le réseau à chaque interface radio de telle sorte que le nombre de canaux distincts dotés aux liaisons adjacentes d'un capteur donné soit au plus égal au nombre de radio interfaces de ce capteur. Les parents et les feuilles sont dotés d'un seul canal statique. Les médiateurs se voient allouer plusieurs canaux orthogonaux de telle sorte qu'ils peuvent switcher dynamiquement à travers les canaux des parents pour collecter les données. Les résultats obtenus montrent que notre approche utilisant un médiateur permet d'obtenir des résultats meilleurs que [RR09] et l'approche utilisant un seul canal en termes d'interférences, throughput, délai de transmission, routing overhead et l'énergie consommée. La Table 6.2 résume les avantages et inconvénients des approches précédentes.

Table 6.2: Résumé des approches précédentes

Approches	Allocation	Avantages	Inconvénients
[MDS10]	Statique	Faible interférence, throughput élevé	Overhead élevé, pas d'économie d'énergie
[WSHL08]	Statique	Faible interférence et latence, throughput élevé	Pas efficace aux conditions dynamiques, connaissance globale
[WM10]	Statique	Faible interférence, routage efficace, adéquat avec les matériaux existants	Pas d'économie d'énergie, overhead élevé
[JDM11]	Statique	Faible interférence, routage efficace	Grande complexité et overhead, pas distribuée
[RR09]	Statique	Routage efficace	Pas d'économie d'énergie, connaissance globale, pas adéquat avec les matériaux existants
[JX11]	Dynamique	Faible interférence, routage efficace, throughput élevé	Overhead et délai élevé
[RBAB06]	Dynamique	Faible interférence, Routage efficace, Adéquat avec les matériaux existants	Pas d'économie d'énergie, overhead élevé
[GGCS10]	Dynamique	Throughput élevé, économie d'énergie, adéquat avec les matériaux existants	Connaissance globale, overhead élevé
[RRT+11]	Hybride	Throughput élevé, faible délai	Pas d'économie d'énergie, connaissance globale
[KV06]	Hybride	Diminution du noeud caché	Pas adéquat en transmissions tous vers un, overhead élevé, impossible d'allouer différents canaux
WCDS-CA (Proposition)	*Hybride*	*Routage efficace, économie d'énergie, faible interférence, pas de connaissance*	*Pas adéquat avec les matériaux existants*

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